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TITLE: MODEL AND SMALL-SCALE TESTS TO EVALUATE THE PERFORMANCE OF DRAG ANCHORS IN COMBINATION

AUTHOR: R. J. Taylor and G. R. Walker

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NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

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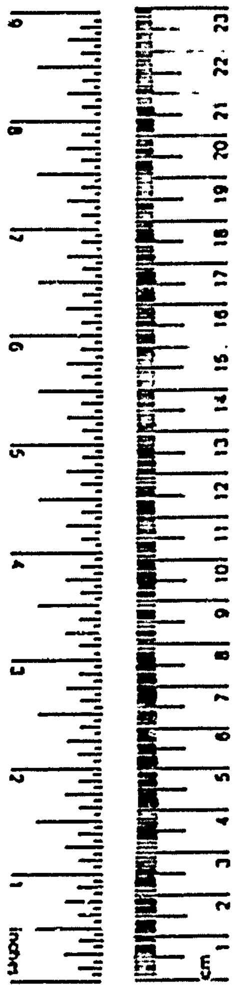
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

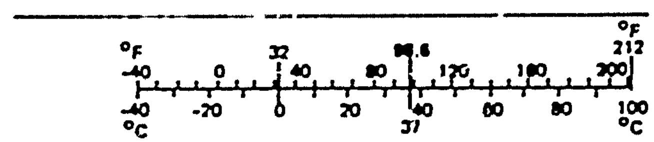
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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UNCLASSIFIED TITLE

MODEL AND SMALL-SCALE TESTS TO EVALUATE THE PERFORMANCE OF DRAG ANCHORS IN COMBINATION.

ABSTRACT

(U) MODEL AND SMALL-SCALE FIELD TESTS OF HIGH EFFICIENCY ANCHORS IN TANDEM (PIGGY BACK) AND IN PARALLEL HAVE BEEN PERFORMED TO EVALUATE THE FEASIBILITY OF USING ANCHORS IN COMBINATION TOO SATISFY EXPANDED NAVY FLEET MOORING REQUIREMENTS. THIS REPORT PRESENTS THE RESULTS OF MODEL TESTS IN SAND AND IN A SYNTHETIC CLAY-LIKE MATERIAL WITH 1/20TH-SCALE MODELS OF A 6,000-POUND STATO ANCHOR AND RESULTS OF TESTS IN BEACH SAND WITH 200-POUND STATOAND 350-POUND DANFORTH ANCHORS. FEASIBLE RIGGING METHODS FOR USING COMBINATIONS OF HIGH EFFICIENCY ANCHORS THAT ARE COMPATIBLE WITH NAVY INSTALLATIONS AND HANDLING CAPABILITY ARE DEFINED. ANCHORS IN TANDEM AND PARALLEL CAN BE ARRANGED TO ACHIEVE SYSTEM CAPACITIES THAT EXCEED THE SUM OF TWO INDIVIDUALLY PULLED ANCHORS. THE INCREASED PERFORMANCE AVERAGES 20% TO 30% AND IS DIRECTLY RELATED TO POTENTIAL COST SAVINGS IN ANCHOR PROCUREMENTS.

PO) TERMS ASSIGNED

ANCHOR PROCUREMENTS
  USE ANCHORS
      PROCUREMENT

HANDLING CAPABILITY
  USE HANDLING

MODEL TESTS
  USE MODEL TESTS

POTENTIAL COST SAVINGS
  USE COSTS
      SAVINGS

SYSTEM CAPACITIES
  USE CAPACITY(QUANTITY)

ANCHORS
  USE ANCHORS

HIGH EFFICIENCY ANCHORS
  USE ANCHORS
      EFFICIENCY
      HIGH RATE

NAVY INSTALLATIONS
  USE INSTALLATION
      NAVY

SAND
  USE SAND

PHRASES NOT FOUND DURING LEXICAL DICTIONARY MATCH PROCESS

PERFORMANCE AVERAGES 20%

1 20TH-SCALE MODELS

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Model and small-scale field tests of high efficiency anchors in tandem (piggyback) and in parallel have been performed to evaluate the feasibility of using anchors in combination to satisfy expanded Navy fleet mooring requirements. This report presents the results of model tests in sand and in a synthetic clay-like material with 1/20th-scale models of a 6,000-pound STATO anchor and results of tests in beach sand with 200-pound STATO and 350-pound DANFORTH anchors. Feasible rigging methods for using combinations of high

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Model and small-scale field tests of high efficiency anchors in tandem (piggyback) and in parallel have been performed to evaluate the feasibility of using anchors in combination to satisfy expanded Navy fleet mooring requirements. This report presents the results of model tests in sand and in a synthetic clay-like material with 1/20th-scale models of a 6,000-pound STATO anchor and results of tests in beach sand with 200-pound STATO and 350-pound DANFORTH anchors. Feasible rigging methods for using combinations of high efficiency anchors that are compatible with Navy installation and handling capability are defined. Anchors in tandem and parallel can be arranged to achieve system capacities that exceed the sum of two individually pulled anchors. The increased performance averages 20% to 30% and is directly related to potential cost savings in anchor procurements.

CONTENTS

INTRODUCTION

Model and small-scale field tests of high efficiency anchors in tandem (piggyback) and in parallel have been performed to evaluate the feasibility of using anchors in combination to satisfy expanded Navy fleet mooring requirements. The Navy has added two new classes of moorings to extend fleet mooring capability from the old maximum of 300,000 pounds (Class AA) to 400,000 pounds (Class BBB) and 500,000 pounds (Class AAA). In addition, there is interest within the Navy to provide moorings in typhoon prevalent areas and for vessels in offshore areas subjected to large waves and high currents. These situations could create loads substantially in excess of 500,000 pounds. This test program was sponsored by the Naval Facilities Engineering Command (NAVFAC).

This report presents the results of model tests in sand and in a synthetic clay-like material with 1/20th-scale models of a 6,000-pound STATO anchor and results of tests in beach sand with 200-pound STATO and 350-pound DANFORTH anchors. Feasible rigging methods for using combinations of high efficiency anchors which are compatible with Navy installation and handling capability are defined.

BACKGROUND

The Naval Civil Engineering Laboratory (NCEL) has completed a comprehensive ocean test program to define the performance of drag embedment anchors at several sites (Ref 1-5). These tests resulted in the development of improved methods for predicting the performance of drag anchors in sand and mud seafloors (Ref 6-10) and in methods for improving the performance of Navy fleet mooring anchors (Ref 7) and other commercially available drag embedment anchors (Ref 6).

Some tests of tandem and parallel anchor arrangements with the STOCKLESS anchor were also performed during the NCEL test program. Anchor arrangements were found that were installable from Navy anchor handling barges and that developed the full capacity of each anchor (Ref 11). With 30,000-pound STOCKLESS anchors, the practical handling limit from most Navy barges, the Navy's fleet mooring requirement, to Class AA (300 kip) in soft clay (mud), to Class AAA (500 kip) in sand, and to Class BB (250 kip) in hard soil can be satisfied. This substantially increased the value of the large Navy inventory of STOCKLESS anchors and reduced the need for anchor procurements. Satisfaction of the remaining anchoring requirements must be accomplished with high efficiency anchors singly and in combination.

An analysis of high efficiency anchoring options for the remaining requirement to 500 kips and for possible requirements to 1,300 kips was performed (Ref 12). The analysis concluded that fleet mooring requirements through Class AAA may be feasible with structurally and operationally improved versions of the Navy STATO anchor in multiples, in sizes to 15 kips, and that very high capacity moorings (to 1,300 kips) may be feasible with high efficiency anchors in multiples, in sizes to 30 kips.

The multiple (tandem and parallel) anchor rigging arrangements that were found suitable for low efficiency Navy STOCKLESS anchors were not necessarily suitable for high efficiency (high capacity to anchor weight ratio) anchors, because high efficiency anchors can be very sensitive to seafloor conditions and rigging arrangement. For this reason, a test program to evaluate combinations of high efficiency anchors was initiated at NCEL. This program considers anchor performance in sand and soft clay. Model tests with a 1/20th-scale model of a STATO anchor were previously conducted in sand and results were presented in an interim report (Ref 12). These tests are summarized in this report and compared to the results of the small-scale beach tests.

ANCHOR TEST PROGRAM

Approach

Since the number of potential anchor rigging arrangements was large, model testing was selected as the best means to rapidly evaluate the options. Small-scale field testing using anchors in 200 to 350 pound size range would then be conducted as needed to further evaluate selected options, define probable performance, and assess the feasibility of these options in full scale.

Laboratory model testing has been and continues to be an effective tool to conduct extensive parametric evaluations of soil-anchor interaction. Results have proven effective in guiding the design of anchors because design changes and soil property changes can be made quickly and the relative effects on anchor capacity can be rapidly assessed. The British Admiralty has used model testing during preliminary design of all its bower and mooring anchors (Ref 13-15). Many other researchers (Ref 16-20) have used model testing to gain a better understanding of anchor behavior, to develop prediction procedures and to enable design improvements to existing anchors.

Model tests were conducted in both sand and mud. Small-scale anchor tests were conducted only in sand. These test data were sufficient to determine feasible options for using high efficiency anchors in combinations for fleet mooring applications. Prototype testing must be done, however, before the optimum rigging arrangements are determined and the preliminary options are used for fleet moorings.

Tandem and Parallel Anchor Rigging Options

The use of anchors in tandem is common in the offshore industry. The standard tandem hookup used in the offshore industry will be referred to in this report as the crown to shackle rigging arrangement; it is shown by Figure 1. For anchors like the STATO where the anchor shank does not protrude through the crown end of the anchor, the rear or piggy-back anchor connects to the anchor crown. In this case, it is necessary to block or weld open the front anchor flukes; otherwise, they will close as the rear anchor assumes load.

Variations to the crown shackle hookup were also evaluated. The first is referred to as the palm to shackle rigging arrangement (Figure 2). Two connection points on the upper palm and two on the lower palm were evaluated. A shank to shackle rigging arrangement, Figure 3, was also evaluated. This method was first suggested by Klaren (Ref 19) and later tested in prototype scale with the STOCKLESS anchor (Ref 2).

The performance of the tandem anchor arrangements was evaluated for a range of anchor separations, from 0 to 8 fluke lengths separation. Anchor separation distances were normalized by anchor fluke length for easy comparison to larger scale tests.

Twin-chain-leg Navy fleet moorings (AA for example) employ anchors in parallel, referred to in this report as the ground ring to shackle arrangement, Figure 4. A variation of this arrangement which staggered the anchors by using different chain lengths from ground ring to anchor was also evaluated.

Test Anchors

Model Tests. One-twentieth scale models of a 6,000-pound STATO anchor (Figure 4) were fabricated for the sand and mud model anchor tests. The holed plate atop the anchor shank was added for the shank to shackle arrangement. The anchor fluke angle was adjustable. It was set at 32 degrees for the sand tests and 50 degrees for the clay tests to correspond to recommended angles for the prototype anchor.

Field Tests. Two anchor types were used during the small-scale anchor tests on the beach at Port Hueneme. Two 200-pound STATO anchors and three 350-pound DANFORTH anchors (Figure 5) were selected because of availability and because these size anchors could be pull-tested with available equipment. The fluke angle for both test anchors was approximately 32 degrees.

Test Apparatus and Procedures

Model Tests - Sand. The sand test tank measured 9.5 feet by 2.5 feet by 1.3 feet deep. Anchors were pulled using a wire wound around a capstan which was driven by a variable speed motor. The test arrangement was very simple but effective. The sand used was a dry, poorly graded, medium density sand that was vibrated to a relative density of 65%. Densification was accomplished using a single vibrator clamped to the side of the test tank. After each anchor test, the sand was thoroughly disturbed and then redensified.

Miniature load cells (Figure 2) were sized to minimize their effect on anchor behavior. Load cells were placed at the shank of each anchor so that for the arrangements shown, the forward load cell recorded total anchoring load (two anchors plus connecting chain) and the rear anchor recorded single anchor load. Drag distance was measured using a deflection pot with a thin cable connected to the forward load cell.

The standard test procedure was as follows: The anchors were dragged from the surface at one end of the tank until the maximum holding capacity for the particular configuration had been obtained. Then, the shank pitch and roll, the chain angle relative to the shank (chain-shank angle), and the shackle depth were recorded. Anchor load and travel were continuously recorded by strip recorder. These data were later digitized using a microcomputer digitizer and processed for later presentation.

<u>Model Tests - Mud</u>. The mud test tank measured 16 feet by 2.5 feet by 2.5 feet deep (Figure 6). The load and deflection measurement systems were the same as those used in the sand test. Problems occurred with the miniature load cells and only two were available during testing. During the tandem tests, one load cell was placed at the forward anchor's shackle and the other was placed at the forward end of the rear anchor line. The capacity of the chain and/or wire, forward of the first anchor, was not measured directly. It could, however, be inferred from the single anchor test results. Equipment problems caused postponement of parallel anchor tests in mud.

The mud test bed is a thixotropic material known as Laponite. It was developed for use in paint products and has the same layered chemical structure as a Hectorite clay. Laponite was selected for this test program because detailed analyses (Ref 21) of Laponite have shown that its behavior can be precisely controlled, it behaves like a clay, and once it is disturbed, it regains strength rapidly. This last feature allows tests to be conducted at a rapid rate.

In determining the properties required for the test soil, the following parameter is generally accepted as sufficient to ensure dynamic similarity:

$$(c/\gamma B)_{prototype} = (c/\gamma B)_{model}$$

where c = shear strength
γ = soil unit weight
B = characteristic length

Based upon the performance of the 6,000-pound STATO prototype, the desired shear strength range was 0 to 0.2 psi for the model test bed. As shown below, this was achieved, and mixing and quality control procedures were derived which allowed duplication of soil properties between tests. The majority of tests were run in soil with an average shear strength of 0.1 psi. Figure 7 presents a typical strength profile. The upper value at each depth represents centerline strength in the tank.

The Laponite was prepared using deionized water and mixed at a concentration of 3% by volume. This resulted in a gel-like material with a water content of about 1100%. Soil sensitivity, which is the ratio of disturbed to undisturbed strength, was approximately 2. Soil strength was completely regained in less than 10 minutes after disturbance.

Before each test, a miniature vane device was used to determine the shear strength at depths from 3 inches to 18 inches in 3-inch increments at various distances across and along the tank. Anchor depth and orientation were recorded at 1 to 2-foot intervals along the tank, while tension and displacement were recorded continuously.

Small-Scale Field Tests - Sand. Tests were performed on the beach at Port Hueneme, which consisted of a poorly graded, fine sand of medium density. Sand compacted by wave action was avoided. Detailed soil property determinations were not made. For these tests, all that was important was that the variability of soil properties over the test area be minor. This was generally confirmed by the consistent performance of single anchors to establish standards for comparison of tandem and parallel anchor performance.

Small load cells (shown in Figure 2) were built to fit within the envelope of 1-1/4-inch chain to prevent interference with the normal anchor embedment process. For the tandem anchor tests, load cells were placed at the forward anchor shackle, at the forward end of the rear anchor line, and between the winch wire and the chain to the tandem anchor assembly. The contribution of the chain forward of the assembly could thus be determined. In the parallel anchor tests, the load cells were placed at the ground ring to record the total chain and anchor loads for each anchor leg.

Anchors were pulled along the beach at about 2 ft/min for drag distances up to 58 feet. Because of the structural limitations of the anchor shackle and/or winch wire, the maximum allowable pulling load was limited to 18,000 pounds. This limitation had to be applied to tests with the 350-pound DANFORTH anchor in some rigging arrangements. Anchor displacement was visually recorded by observing the travel of a marked line attached to the rear anchor relative to a fixed point. Values were marked directly on the oscillograph record. At the completion of each test, the anchors were uncovered and anchor shank pitch, anchor roll, anchor embedment depth, and chain angle at the shank connection were recorded.

RESULTS AND DISCUSSION

Model Tests - Sand

For comparison purposes, the holding capacity of a single 1/20th scale model STATO anchor with a wire mooring line was established as the standard holding capacity; the value was 15.9 pounds. The holding capacity of the various tandem and parallel anchor arrangements tested was then compared to the standard and referred to as the relative anchor capacity. This provides a measure of the effectiveness of the various anchoring arrangements.

Crown-Shackle Arrangement. An example of the test results for a crown-shackle rigging arrangement for anchors spaced at a distance equal to 6.34 fluke lengths is presented in Figure 8. A minimum of two tests were run for each setup. In this plot, rear and forward anchor loads are individually shown. Results are plotted as normalized single anchor capacity versus normalized drag distance. Anchor capacity is referenced to the standard capacity of 15.9 pounds.

Figure 8 shows that the forward anchor behaved as a single anchor, developing peak capacity in a drag distance of about 8 fluke lengths. The rear anchor also behaved as a single anchor until it was dragged into the soil disturbed by the forward anchor. At that point, rear anchor capacity increased substantially to where it was holding about 1.7 times the standard capacity (in this particular test). This increase began at about 8 fluke lengths of drag which is approximately equal to the distance between the anchor fluke tips for a chain length equal to 6.34L (L = fluke length). In the disturbed soil, the rear anchor penetrates deeper than normal because bearing resistances that hinder embedment on anchor and chain are reduced. As embedment increases in sand, the anchor capacity increases.

The effectiveness of the rear anchor in the crown-shackle setup is further illustrated in Figure 9. Rear anchor load as a percentage of the total tandem anchoring load is plotted versus normalized drag distance for representative tests. All 42 tests plotted within the data bound shown. After about 10 fluke lengths of drag, the rear anchor has penetrated the soil disturbed by the forward anchor and its capacity reaches a reasonably constant percentage of the total load; the average was about 60% for all spacings tested.

Summary results for the crown-shackle rigging arrangement are shown in Figure 10. These results are for the case where the rear anchor penetrates the soil disturbed by the forward anchor. The rear anchor load cell could not be used for spacings less than about 1 fluke length; only the forward load cell which recorded total load was used. While the results show that the optimum anchor spacing is quite small, about 1/2 fluke length, general use of such small spacings for fleet moorings is not very practical because this would require both anchors to be handled simultaneously. There are conceivable situations, however, where the added handling complexity could be outweighed by the added effectiveness of the close-spaced tandem arrangement.

The total relative anchor capacity approaches a conservative minimum of 2.5 for an anchor separation of about 9 fluke lengths or more. At this point, the forward anchor is performing as an individual anchor and the rear anchor is about 50% more efficient than an individual anchor. Practically, after an anchor separation of 2 fluke lengths, this minimum is nearly achieved.

Palm-Shackle Arrangement. Four chain connection locations on the STATO anchor palm were used during testing, two each on the upper and lower palm. The location had little effect on the results as shown in Figure 10, where the summary data were plotted and are compared to the crown-shackle data. At small anchor spacings, total anchor capacity was less, while at the 4-fluke-length spacing, the behavior was similar. This method caused anchors to be somewhat more unstable during drag than the crown-shackle method. Since there are no substantial performance or operational advantages with the palm-shackle method, it was not pursued further.

Shank-Shackle Arrangement. Test data are plotted in Figure 11 and compared to the crown-shackle method. The distribution of load between anchors was not consistent, particularly as the anchors' separation was decreased. This was caused by the elevated chain-shank angle created as the chain rode over the forward anchor palm. Rear anchor embedment and thus capacity were reduced. Also, the forward anchor's stability was affected by slight off-line loading by the rear anchor which introduced a rotational moment at the shank connection point. The instability worsened as the chain was connected closer to the forward anchor shackle. This rigging method is more complex than the others evaluated, and since there seems to be no obvious performance advantage, it is not recommended.

Ground Ring-Shackle Arrangement. This method is schematically illustrated in Figure 12 as a guide to the results in Figures 12 through 14.

Ground ring-shackle summary test results are shown in Figure 12. The separation of each anchor relative to anchor fluke length was varied from $L_1 - L_2$ equals 0 (anchors side by side) to 3.4 fluke lengths (3.4L). At $L_1 - L_2 = 0$, the two anchors are less effective than the sum of two individual anchors. In this case the total relative capacity is 1.75. This equates to a 12-1/2% system performance reduction caused by anchor interference which causes the anchors to roll and lose capacity. This behavior is illustrated in Figure 13 and shown graphically in the left half of Figure 12. As the anchor separation in the fore and aft direction increases ($L_1 - L_2$ increases), the total anchor capacity increases and approaches a relative value of 2.5 at $L_1 - L_2 = 4L$; this is a 43% improvement in total anchor capacity compared to side by side anchor performance. This maximum relative anchor capacity for parallel anchors agrees with the minimum found for the previous tandem arrangements; see Figure 14. At $L_1 - L_2 = 4L$, the parallel STATO anchors are separated by about 2 fluke lengths (the shank length is about equal to 2 fluke lengths) in the fore and aft direction at maximum drag distance. At this separation, the anchors behave as a tandem arrangement with the forward anchor eventually disturbing the soil and enhancing rear anchor capacity.

The lateral separation of test anchors was varied between 1.7L (stabilizers touching) and 5L. The latter separation is roughly equal to 50 feet for a 12,000-pound STATO. Fifty feet is typical for twin-chain-leg fleet moorings. The lateral separation did not affect test results. Maximum capacity occurred when the anchors moved as close as possible to each other.

Summary - Model Tests in Sand. Of the tandem STATO anchor arrangements evaluated, the crown-shackle arrangement resulted in the most uniform system performance. Neither anchor exhibited any tendency for instability, and each anchor developed at least its standard capacity, the capacity it would have achieved if it had been dragged singly. This arrangement resulted in a system capacity that was 25% more efficient than the sum of two individual anchors.

Tandem anchor connection through the forward anchor tripping palm or shank was generally effective; however, connection and/or installation is more difficult and instabilities were sometimes noted in the forward anchor. These methods would thus be field-tested only if the crown-shackle method proved ineffective.

The ground ring-shackle or parallel anchor rigging method is standard for twin-chain-leg Navy fleet moorings. Results show that when the anchors are placed side by side, the ultimate capacity of this system is about 12% less than the sum of the individual anchors due to anchor interference which causes anchor instability. Simply by longitudinally separating the anchors by a minimum of 2 fluke lengths, the ultimate system capacity increases by about 40%.

As shown, tandem and parallel model anchor system capacities can exceed twice the capacity of an individual anchor in sand. This was caused principally by enhanced rear anchor capacity as it was dragged into the sand disturbed by the forward anchor. This finding should be field validated because of the potential for substantial anchor weight savings and because the potential higher system capacities must be considered when sizing mooring legs.

Small-Scale Field Tests - Sand

The details of the 28 tests conducted on the beach at Port Hueneme are provided in Table 1. Anchor and anchor system capacities, various angle and penetration measurements, mooring line and anchor characteristics, and keys to the measurements are listed for comparison. Ten of the tests listed were single anchor tests to define standard anchor capacities for comparison to tandem and parallel anchor tests.

Standard Anchor Capacities. Four tests were run with the 200-pound STATO with chain; results are plotted in Figures 15 and 16. The lower curve (test 6-17-83) in these figures was not used to determine the standard capacity. In this test, anchor embedment was restricted by a very dense sand/gravel layer. The standard capacity of the anchor alone when dragged with a chain mooring line was 4,250 pounds. The standard capacity of the anchor and chain system was 4,800 pounds. Two hundred pounds of chain held almost three times its own weight or roughly 3 times what it held when dragged freely on the surface.

Of the four tests, the highest capacity occurred in test 6-20-83-01. This test differed from the others in that the anchor flukes were fixed fully open at 32 degrees. The other single STATO test anchors had freely movable flukes. The flukes did open quickly but after the test it was found that some sand was wedged between the anchor shank and the wedge insert which controls fluke angle. This caused up to a 3 to 5-degree added fluke angle reduction, resulting in fluke angles of 27 to 29 degrees. This, according to fluke angle test runs by Towne (Ref 22), could be sufficient to cause the approximate 6% difference in fixed and movable fluke capacity.

Three tests were run with a 7/8-inch wire line to the fixed fluke STATO anchor (Figure 17). The standard capacity of the anchor was 5,000 pounds. The wire provided little or no measurable added capacity. The standard capacity for the anchor-wire system is similar to the capacity of the anchor-chain system except that the load distribution is different. These results differ somewhat from the laboratory model test results (Ref 12). In the laboratory, the anchor-chain system held more than the anchor-wire system because the chain disturbed the soil forward of the anchor shank, and allowed deeper anchor penetration with resulting higher capacity.

Three tests were run with the fixed fluke DANFORTH (32-degree fluke angle) and results are presented in Figure 18. The standard or mean capacity for the 350-pound DANFORTH is 12,500 pounds. The added capacity from the chain was small, on the order of 500 pounds, or roughly 4% of the total load.

Tandem STATO Anchors. Tests were performed at tandem anchor spacings of 0.92 fluke length (L), and 2L, 5.1L and 10.4L. Figure 19 shows the STATOs in tandem at a spacing of 2 fluke lengths. The summary results of these tests are presented in Figure 20. This presents anchor capacity, relative to the standard STATO capacity of 4,250 pounds, versus anchor separation. At a relative capacity of 2, the tandem anchor system would be as effective as two individually pulled, 200-pound STATO anchors. Model test results are plotted for comparison. Generally, past 2 fluke length spacing (2L), the results are consistent. Practically, the difference at less than 2L is unimportant because this would not be a reasonable rigging arrangement for field use. The data show the positive influence of the anchors on one another.

The performance gain of the tandem system is caused by two things. The rear anchor chain provides a downward loading component on the forward anchor at close anchor spacing, causing deeper anchor burial. At greater anchor spacings, this component is less; thus, the forward anchor contribution to system performance decreases. This is shown by the lower portion of Figure 20. Once the rear anchor moves into the soil disturbed by the forward anchor, it is able to penetrate deeper with resulting higher capacity. This effect becomes more pronounced as anchor separation increases because the rear anchor can behave more independently. Figure 20 shows the rear anchor assuming a higher percentage of the system load with larger anchor spacing. Figure 21 illustrates the effect on the rear anchor as it moves into disturbed soil. At 5.1L anchor spacing, the anchor fluke tips are about 7 fluke lengths apart. The tandem anchor system achieved an initial maximum capacity at a drag distance of about 4L. Load then dropped off until the rear anchor encountered the disturbed soil; then, capacity increased rapidly. For this test, the capacity at the maximum test drag distance (16L) was more than 30% greater than the initial peak.

Table 2 provides data which further illustrates the tandem system behavior. The mean depth of embedment of the anchor crown was 5.1 inches for a single STATO anchor. When used in tandem, the mean depth of embedment increased to 7.25 inches for the forward anchor and 9 inches for the rear anchor. The standard deviations, thus confidence level, for these three measurements were comparable.

According to the field as well as the model results, the crown-shackle tandem arrangement using structurally improved STATO anchors should be an effective rigging method. The system capacity should exceed the capacity of the anchors if pulled individually. The system performance gain could be up to 25% in sand. This would result in a 25% anchor weight savings.

Tandem STATO-DANFORTH Anchor Combinations. Several tests were performed with STATO and DANFORTH anchors in combination to see whether the tandem STATO results could be more generally applied. Two combinations were evaluated, one with the STATO in front with the DANFORTH piggybacked and one with the DANFORTH in front (Figure 22). The stability characteristics of these anchors is not the same. The STATO is a more roll stable anchor; it will maintain its maximum achieved capacity with drag.

The DANFORTH anchor is a better penetrator than the STATO anchor in sand and its center of fluke area and, thus, the center of pressure on the anchor is nearer the shank-crown connection point. These characteristics mean that the STATO should be more stable than the DANFORTH anchor. Table 2 shows the substantial difference between STATO and DANFORTH anchor crown embedment depth, 5 inches compared to almost 18 inches for the DANFORTH. In sand, crown depth is approximately independent of anchor weight for the same anchor type. Thus, the comparisons for the different weighted STATO and DANFORTH anchors should be valid. The difference in the centers of pressure for the two anchors is reflected in the beta (β) angles also listed in Table 2.

The beta angle is the difference between the chain angle and the shank angle. A 0-degree beta angle would mean that the chain was directly in line with the axis of the shank and that the anchor's roll axis was along the shank. As the beta angle increases, the center of pressure on the anchor moves closer to the anchor fluke tip. This promotes anchor stability. The beta angle for the single STATO was 8.9 degrees, while it was 5.1 degrees for the DANFORTH anchor. The variation in beta was greater for the DANFORTH. In tandem, the beta angle for the forward STATO reduced by over 3 degrees to 6.6 degrees. This is due to the added external load by the rear anchor chain. No measurements were possible with the forward DANFORTH because of its rapid roll, but it is clear that its center of pressure would move up towards the shank, reducing anchor stability.

The results of the tandem tests are presented in Figures 23 and 24 as plots of holding capacity versus normalized drag distance. With the DANFORTH in front (Figure 23), total tandem load was substantially less than the single capacity of a DANFORTH anchor. The DANFORTH rolled rapidly at about 5 fluke lengths of drag, achieving less than half of its single anchor capacity. The STATO in the rear remained stable and achieved its single anchor capacity. It was not pulled far into the disturbed soil caused by the DANFORTH. The vertical stabilizer for the rolled DANFORTH is shown in Figure 25. With the STATO in front and the DANFORTH in the rear, the results were quite different. Both anchors were stable and developed at least their single anchor capacities. The test was stopped at 17,000 pounds of load because of safety considerations, but load was still increasing.

Summary results for the combinations are presented in Figure 26. Total anchor load referenced to the standard capacity, which in this case is defined as the total standard capacity of the two anchors, is plotted against normalized drag distance. The performance difference is extreme. This illustrates the need to ensure that the forward anchor in a tandem arrangement is very stable. If the stability is questionable, it may be necessary to overstabilize the anchor by increasing the length of the stabilizers to prevent roll.

These results in sand provide a picture of what might happen in a mud seafloor with anchors in tandem. Anchor stability decreases with soil strength and soil strength variation with depth. Anchors unstable or marginally stable in sand will be unstable in mud. Results of the NCEL test program (Ref 1, 2, 3, 5, 12) verify this. Also, the load applied to the forward anchor by the rear anchor in tandem further exaggerates forward anchor instabilities. Anchors with demonstrated stability, such as the STATO and BRUCE TS, will provide reasonable tandem anchor options for mud and sand.

Parallel Anchors. The summary results for all parallel anchor tests are provided in Figure 27 with the model test results shown for comparison. The field data became more consistent as the anchor fore and aft separation distance increased. The model data were consistent throughout. In the side-by-side condition, the typical twin-chain-leg Navy fleet mooring configuration, the anchor capacity ranged from a low of 1.75 times the standard single anchor capacity to 2.3 times the standard capacity. With further dragging, the STATO anchors would have continued to come together, further reducing the total capacity.

The two tests with the DANFORTH anchors side by side are also shown. This is shown as a -2L anchor separation in Figure 27. This allows comparison to the tandem tests where separation is measured from rear anchor shank to forward anchor crown. Had all of the side-by-side data been averaged rather than just the STATO data, the curve would have been significantly lower. Regardless, the side-by-side anchors do interfere with one another; this interference is shown in Figure 28 for the STATO and DANFORTH anchors. These photographs represent the final or near final positions of the anchors at ultimate drag. With a larger lateral separation, the anchors would have achieved a higher initial capacity, but the residual capacity at ultimate drag would be the same as shown by Figure 27.

As anchor separation in the fore and aft direction increases, the behavior of the parallel anchors approached tandem anchor behavior. Figure 29 shows the performance of parallel STATO anchors at a 5.8-fluke-length spacing. The curves are similar to those presented for tandem anchors, as shown in Figure 21. Anchor and total anchor load have almost peaked at 7 fluke lengths of drag. At that point, the rear anchor begins to encounter the soil disturbed by the forward anchor. Total load then increases by about 25% to 10,000 pounds for this test.

When the rear anchor approaches the disturbed zone, it rolls down into the trough created by the forward anchor. This is shown by the photograph in Figure 30. The optimum anchor separation is greater than 6 fluke lengths. In the laboratory, 2-fluke-length spacing was the minimum required. The prototype value could be as much as a 10-fluke-length spacing.

Summary - Small-Scale Field Tests in Sand. The field and model test results for tandem and parallel anchors are summarized in Figure 31. The field and model test results were generally in agreement; the trends were quite similar except for tandem anchors at spacings less than 2 fluke lengths.

The field tests confirmed that the crown-shackle tandem rigging arrangement was an effective means of tandem anchoring for STATO anchors. System capacity was 20 to 25% greater than would be anticipated based on the capacity of individually pulled anchors.

Results also showed that not all anchors are suitable for use in tandem. The DANFORTH anchor which is less stable than the STATO-type anchor became very unstable when load from the rear anchor was applied to the forward anchor. This caused system capacities far less than the capacity of a single DANFORTH anchor.

The performance of anchors in parallel when side by side was quite variable. The anchors eventually interfere with one another, causing a reduction in system capacity. By staggering the anchors, anchor interference was eliminated and system capacity was enhanced by up to 15 to 20% greater than the sum of the single anchor capacities.

At anchor spacings of greater than about 6 fluke lengths, tandem and parallel anchor system capacities become similar. Both show system capacities greater than would be expected from single anchors. The majority of the load increase comes from the rear anchor as it is dragged into the zone disturbed by the forward anchor.

Model Tests - Mud

Thirty-five single and tandem anchor tests were conducted in mud. Summary results of these tests are given in Table 3. Fourteen of the tests listed were single anchor tests which were conducted to define standard anchor capacities for comparison to tandem anchor results.

Standard Anchor Capacity. Anchor capacity varied with soil shear strength from a high of 21.6 lb at .2 psi to about 10 lb at .08 psi. Within the desired soil strength range of 0.08 to 0.11 psi, anchor capacity randomly varied from 9.7 to 12.7 lb with a median value of 11 lb. This value was independent of mooring line type which would be expected in a uniform strength test bed. The similarity in the holding capacity of anchors with chain and wire lines is shown in the lower half of Figure 32. Although anchor capacities were comparable, overall performance was not. The mooring line altered the trajectory of each anchor, shown in the upper half of Figure 32. Anchor embedment was inversely proportional to line size. The maximum anchor embedment with wire was actually determined by the tank depth and/or the limited pull distance available.

The mooring line plays a significant role in anchor behavior and can provide a substantial part of total anchoring capacity. Figure 33 shows anchor plus chain capacity as well as anchor capacity. The chain provides 20 to 30% of the total load. This is comparable to what was found during field trials (Ref 1 through 5). Model anchor performance also agreed well with the predictions made with the NCEL anchor performance models (Ref 10) which were based on the field test results.

The anchor performance model for cohesive soil is based on slip line theory where:

$$H_c = S_u N_c A$$

where H_c = anchor holding capacity (lb)

S_u = soil undrained shear strength (psf)

N_c = anchor holding capacity factor (dimensionless)

A = anchor fluke area (ft^2)

The holding capacity factor, N_c, was determined through prototype testing and it varied widely between anchor type (between $N_c = 4$ to 15) but did not vary appreciably with anchor size for each anchor type. Analysis of Navy field tests of the STATO anchor results in the selection of $N_c = 13$ which represented the median value. The median value for the single model STATO anchor was 11.8. The standard deviation for the 14 tests was only 1.5; thus, model anchor performance was uniform. The laboratory and field test data agree quite well, therefore, tandem anchor performance should be reasonably representative of field performance.

Tandem Anchor Capacity. Seventeen tandem tests were conducted with tandem anchor spacings of 0.67 fluke length (L) to 8.1L with various size mooring and anchor separation lines.

Initially, it was intended to use a wire mooring line and then vary the separation line type and length but this proved impractical because of the unexpectedly large tandem system penetrations that occurred. The anchors rapidly penetrated to the bottom of the tank, thus, maximum loads could not be defined. Figure 34 shows the trajectory of two tandem anchor systems with a tandem spacing of 0.67L. The steepest trajectory occurred with the wire mooring line - large chain separating line system (test 8-11-83-01). The change to a large chain mooring line caused a slight decrease in the trajectory slope but still it was not acceptable. The trajectories of a single anchor with wire and chain mooring lines are shown for comparison. The difference in single and tandem anchor trajectories dramatically illustrates the potential effectiveness of tandem anchor systems composed of stable anchors.

To properly evaluate tandem anchor system behavior it was necessary to eliminate tank depth as a variable. This was done by increasing the size of the mooring line to reduce anchor system penetration and to ensure that the system achieved its maximum penetration depth without encountering the tank base. This was accomplished by using the large chain doubled between the wire and forward anchor. Results of a typical test are shown in Figure 35 where tandem anchor spacing was 5.2 fluke lengths. The single test shown for comparison in Figure 35 used the same double large chain - wire mooring line as used in the tandem test.

In this test, there was very little difference in the trajectory of the forward anchor. This was typical when tandem anchor spacing exceeded about 5 fluke lengths. The influence of the rear anchor on the forward anchor diminishes with anchor spacing.

With the doubled large chain mooring line segment, peak anchor system load was achieved before the anchors reached the base of the tank. Load versus drag distance for three tandem tests with similar mooring line makeup at different anchor spacings is shown in Figure 36. Although trajectories and load distribution between anchors was different, total load measured at the forward anchor shackle was not. For comparison, two other curves are presented. The relationship for the tandem system with wire mooring line is comparable to the others shown even though its embedment and trajectory (refer to Figure 34) were considerably greater. The single anchor capacity peaks at about 12 lb, less than half tandem capacity.

Summary data for all tandem tests with the doubled large chain mooring line segment are shown by Figure 37. This shows total anchor load relative to total standard load versus anchor separation. From this figure, it is clear that two anchors in tandem can be more efficient than individually pulled anchors. The improvement ranged from 10 to 50%. Also, it did not make much difference what the anchor separation was or what separation line was used; results fell within the same general band.

Anchor roll was monitored during tests. For these tests, the minimum roll occurred at about 5 fluke lengths spacing which coincides with the same spacing where maximum system capacity typically occurred. This is shown as the apex of the test band in Figure 37. As anchor spacing decreased, the rear anchor tended to roll more than the forward anchor. This reversed as anchor spacing increased beyond 5 fluke lengths. It is unclear at this time whether this was caused by anchor interferences or variations within the test tank.

Summary - Model Tests In Mud. The performance of the model anchors agreed well with performance predictions made with the mathematical model developed from NCEL's field test program. This significantly improves the credibility and extrapolatability of the model tandem anchor tests.

In the uniform soil test bed used in this program, single anchor capacity was relatively independent of anchor line type and size. However, anchor trajectory was significantly affected as would be expected. Anchor embedment depth was inversely proportional to anchor line size.

Tandem anchor systems rigged with the crown to shackle method were effective in the soft test mud. System capacity was 10 to 50% greater than could be expected based upon the performance of individually pulled anchors. System capacity was not very sensitive to mooring line type and anchor spacing.

The tests clearly show that the crown-shackle, tandem rigging technique with STATO type anchors is feasible and deserves prototype evaluation.

CONCLUSIONS AND RECOMMENDATIONS

The primary goal of this investigation has been to evaluate the feasibility of using anchors in multiples to satisfy expanded Navy fleet mooring requirements. Feasibility has been established with the identification of effective tandem and parallel anchor rigging methods and suitable anchor types. Anchors in tandem and in parallel can be arranged to achieve system capacities that exceed the sum of two individually pulled anchors. This increased performance averages 20% to 30% and is directly related to potential cost savings in anchor procurements. In addition, the ability to use small anchors in multiples to develop capacities equivalent to much larger single anchors means that the Navy's overall anchoring capability has the potential to expand without an increase in the Navy's handling assets.

Prototype evaluation will be required to validate and calibrate the lab and small scale field results to enable safe mooring leg design before these systems are used for fleet moorings. Extrapolation based upon the present test data to prototype performance for anchor sizes that could approach 15,000 to 30,000 lb would have to be highly conservative. Also, installation and recovery procedures for these high performance anchor systems must be defined to ensure that the installed systems function as intended and that they are retrievable.

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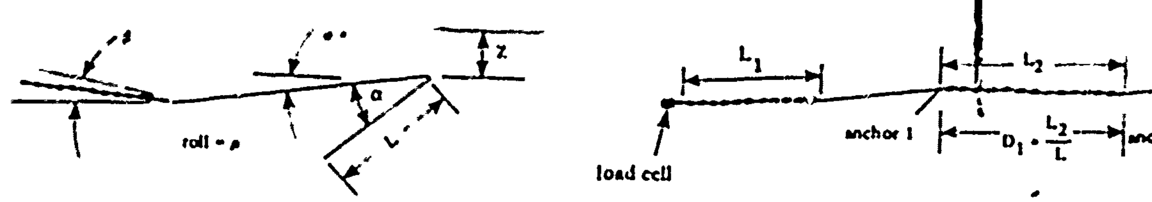
Table 1. Summary Data for Small-Scale Tests on the Beach at Port Hueneme

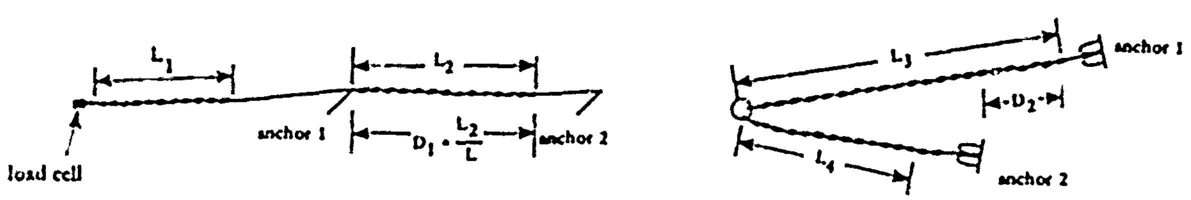
Test No.	Test Type	Anchor 1 Type	Anchor 1 Weight (lb)	Anchor 2 Type	Anchor 2 Weight (lb)	Peak Load (lb) Cell 1	Peak Load (lb) Cell 2	Peak Load (lb) Cell 3	Peak Load Drag Distance (ft)	Anchor 1 β (deg)	Anchor 1 [illegible] (deg)	Anchor 1 φ (deg)	Anchor 1 z (in.)	[illegible] (de
[illegible]	single	STATO	200			4,?00	4,330		16	[illegible]	-1	4	5	
[illegible]	↓	↓	↓			4,000	3,600		20	[illegible]	-1	0	2-1/2	
[illegible]						4,673	4,100		20	11	0	0	1-1/4	
[illegible]						5,000	4,500		14	11	-1	1	3-3/4	
[illegible]						5,200	5,050		12					
[illegible]						5,150	5,050		24	9	-6	4	3-1/4	
[illegible]	↓	↓	↓			5,000	5,000		32	10	-3	1	3	
[illegible]	tandem	STATO	200	STATO	200		9,600	5,000	30	9	1	3	6	0
[illegible]	↓	↓	↓	↓	↓	10,000*	9,100*	4,670*	24					
[illegible]	single	DANFORTH	350			11,900	11,330		28	6	10	1	12	
[illegible]							10,000		30	5	5	2	11	
[illegible]	↓	↓	↓				11,000*		18	8	4	3	16	
[illegible]	tandem	STATO	200	STATO	200		11,?00*	6,400*	24	4	1	3	11	5
[illegible]							11,350	5,660	28	4-1/2	2	0	8	8
[illegible]							10,300*	5,300*	30	6	2	1	6	6
[illegible]							11,400	5,900*	40	9	2	3	6	6
[illegible]	↓	↓	↓	↓	↓		10,300	5,750	36	10	2-1/2	1	5-1/4	8-1
[illegible]	tandem	DANFORTH	350	STATO	200		9,330	4,250	10			55		
[illegible]	↓	↓	↓	↓	↓		10,800	4,750	10			45		
[illegible]		STATO	200	DANFORTH	350		17,000*	17,000*	20	3-1/2	3-1/2	1	8	
[illegible]	parallel	STATO	200	STATO	200	8,660	3,700	4,330	30	2-1/2	-2	-4		8
[illegible]						11,200	5,600	4,600	36			-11		
[illegible]						11,100	5,660	4,800	32	10	0	-16	9	8
[illegible]						10,600	5,200	5,000	40	10	0	-16	7-1/2	9
[illegible]						10,000	5,150	4,000	30	9	1	-10	8	6
[illegible]	↓	↓	↓	↓	↓					7	0	-16	8	
[illegible]	parallel	DANFORTH	350	DANFORTH	350					3	9	-22	23	5
[illegible]	↓									1-1/2	6	2	16	7

Key to Measurements



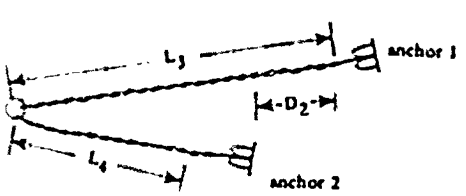
[illegible] of Small-Scale Tests on the Beach at Port Hueneme

[illegible] cell	Peak Load [illegible]	Anchor 1 δ (deg)	Anchor 1 θ (deg)	Anchor 1 ρ (deg)	Anchor 1 z (in.)	Anchor 2 δ (deg)	Anchor 2 θ (deg)	Anchor 2 ρ (deg)	Anchor 2 z (in.)	Anchor Separation (fluke lengths, L) D_1 or D_2	Mooring Line Characteristics: Anchor 1	Mooring Line Characteristics: Anchor [2]
	[illegible]	9	-1	4	5						L_1 [20'8"-1" chain]	—
	[illegible]	7	-1	0	2-1/2						↓	—
	[illegible]	11	0	0	1-1/4						↓	—
	[illegible]	11	-1	1	3-3/4						↓	—
	[illegible]										L_1 [50'-7/8" wire]	—
	[illegible]	9	-6	4	3-1/4						↓	—
	[illegible]	10	-3	1	3						↓	—
[illegible]	[illegible]	9	1	3	6	0	0	2	5-1/2	0.92	L_1 [20'8"-1" chain]	L_2 [23"-load cell]
[illegible]	[illegible]									0.92	↓	↓
	[illegible]	6	10	1	12						↓	—
	[illegible]	[illegible]	9	2	11						↓	—
	[illegible]	7	4	1	16						↓	—
[illegible]	[illegible]	9	1	1	11	5	1	-8	14	2	↓	L_2 [2'2"-3/4" cha
[illegible]	[illegible]	4-1/[illegible]	2	0	8	8	0	1	9	2	↓	↓
[illegible]	[illegible]	6	2	1	6	6	-2	2	6-3/4	5.1	↓	L_2 [10'2"-3/4" ch.
[illegible]	[illegible]	9	2	3	6	6	-2	2	8-1/2	5.1	↓	↓
[illegible]	[illegible]	10	2-1/2	1	5-1/4	8-1/2	-4-1/2	2	7	10.4	↓	L_2 [21'5"-3/4" ch.
[illegible]	[illegible]			55				0		5.1	↓	L_2 [10'2"-3/4" ch.
[illegible]	[illegible]			45				0			↓	↓
[illegible]	[illegible]	9-1/[illegible]	3-1/2	1	8		4	1	23-1/2		↓	↓
[illegible]	[illegible]	-1/[illegible]	-2	-4		8	-3	4		~2	L_3 [50'-7/8" wire]	L_4 [50'-7/8" wire]
[illegible]	[illegible]			-11				9		~2	L_3 [27'-3/4" chain]	L_4 [27'-3/4" chain]
[illegible]	[illegible]	10	0	-16	9	8	-1	5	5	1.5	L_3 [27'-3/4" chain]	L_4 [20'-3/4" chain]
[illegible]	[illegible]	10	0	-16	7-1/2	9	-1	4-1/2	3	1.5		↓
[illegible]	[illegible]	9	1	-10	8	6	0	6	2	5.8	L_3 [35-1/2'-3/4" chain]	↓
		7	0	-16	8		3	5	6-1/4	5.8		
		3	9	-22	23	5	14	11	19-1/2	~2	L_3 [24'-3/4" chain]	L_4 [24'-3/4" chain]
		1-1/[illegible]	6	2	16	7	10	6	24-1/2	~2		



2

[illegible]		Anchor Separation (fluke lengths, L) D_1 or D_2	Mooring Line Characteristics		Comments
[illegible]	[illegible]		Anchor 1	Anchor 2	
			L_1 [20'8"-1" chain]	—	Free flukes (F)
				—	(F) - Dense sand/gravel layer encountered
				—	
				—	Fixed open flukes
			L_1 [50'-7/8" wire]	—	all remaining tests
				—	
				—	
[illegible]	[illegible]	[illegible]	L_1 [20'8"-1" chain]	L_2 [23"-load cell & fittings]	
		[illegible]			Anchor hit rock - bent fluke tips
				—	
				—	
				—	
[illegible]	[illegible]	[illegible]		L_2 [2'2"-3/4" chain]	
	[illegible]	[illegible]			
	[illegible]	5.1		L_2 [10'7"-3/4" chain]	
[illegible]	[illegible]	5.1			
[illegible]		[illegible]		L_2 [21'8"-3/4" chain]	
		5.1		L_2 [10'7"-3/4" chain]	
[illegible]	[illegible]				
[illegible]		[illegible]	L_3 [50'-7/8" wire]	L_4 [50'-7/8" wire]	44" spacing between crowns at test end
[illegible]		[illegible]	L_3 [27'-3/4" chain]	L_4 [27'-3/4" chain]	33" spacing between crowns at test end
	[illegible]	1.5	L_3 [27'-3/4" chain]	L_4 [20'-3/4" chain]	
[illegible]	3	1.5			
	[illegible]	[illegible].8	L_3 [35-1/2'-3/4" chain]		
	6-1/4	[illegible] 6			
	19-1/2	[illegible]	L_3 [24'-3/4" chain]	L_4 [24'-3/4" chain]	
	24-1/2	[illegible]			



3

Table 2. Performance Characteristics of Test Anchors During Beach Tests

[Refer to Table 1]

Anchor	Relative Chain Angle, β (deg)			Anchor Crown Embedment, z		
	Number of Data Points, n	Mean, $\bar{x}$	Standard Deviation, s	n	$\bar{x}$	s
Single STATO	15	8.9	1.77	10	5.1	2.36
Single DANFORTH	7	5.1	2.2	6	17.7	5.6
Tandem STATO - forward anchor	7	6.6	2.7	5	7.25	2.33
Tandem STATO[a] - rear anchor	5	6.7	1.5	5	9	2.9

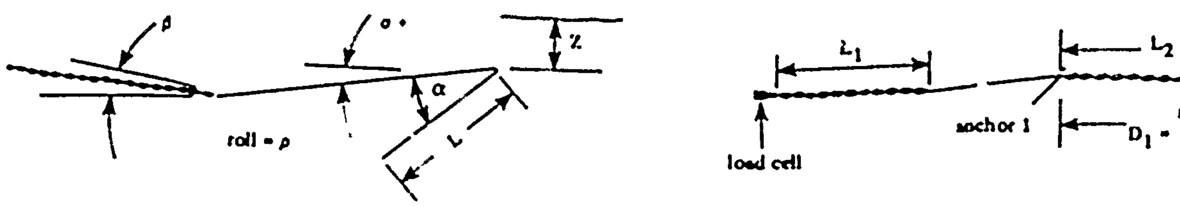
[a]Value at 0.92 fluke length. Anchor is not included; it is not considered representative.

Table 3. Summary Data for Model STATO Tests in Mud

Test No.	Test Type	Peak Load (lb)		Drag Distance at Peak Load (ft)	Soil Shear Strength at z_{max} (psi)	Holding Capacity Factor[a] N_c	Anchor 1			Anchor 2			Anchor Separation, D_1 (Fluke Lengths, L)
		Cell 1	Cell 2				β (deg)	z (in.)	θ (deg)	β (deg)	z (in.)	θ (deg)	
8-9-83-01	Single	21.6		9	.2	9.9	42	10.25	---				
-02		11.5		8	.11	9.9	16	11.75	---				
8-10-83-01		10.3		8	.08	12.05	-26	7.4	14				
-02		9.7		8	.076	11.8	-37	6.6	14				
-03		11.0		8	.08	12.8	-26	7.25	18				
-04		11.0		8	.08	12.9	-48	5.4	16				
-05		11.0		10	.075	13.6	-31	13.38	20				
-06		10.5		8	.08	12.3	-19	11.75	18				
8-10-83-07	Tandem	29		12	.09	15	---	---	---	-13	19.75	22	6.6
8-11-83-01		22		6	.11	9.3	-21	19.75	20	-26	21.5	13	0.67
-02		32		10	.115	13	-48	19.25	27	-46	21.9	20	0.67
8-11-83-03	Single	8.8		4	.078	10.6	-46	6.75	17				
-04		12.5		6	.099	12.3	-37	7.9	17				
-05		10.6		10	.09	11	-19	8.5	27				
8-11-83-06	Tandem	23.6		10	.085	13	7	12.4	26	-36	15.5	20	1.8
-07		19.5		6	.08	11.4	-23	8.5	19	[illegible]	12	25	
8-12-83-01		27.6		10	.096	13.5	60	10.75	23	-10	12.4	-3	2.2
-02		28.5		10	.093	14.3	-88	6.0	11	-46	12.8	22	3.9
-03		28.2	18	10	.1	13.2	-29	9.5	27	-34	15.8	19	
-04		26.8		10	.1	12.5	-23	9.5	17	-36	15.1	16	5.2
8-16-83-01		32.9		10	.105	14.2	-39	9.5	20	-7	16.5	15	
-02		28	13.4	8	.1	13.1	51	6.6	16	-58	13.9	20	8.1
-03		26	13.2	8	.1	12.9	29	6.9	15	-31	14.2	16	
-04		30		8	.1	14	-37	7.2	15	-36	15.1	16	
-05		28.8		8	.0925	14.5	-2	7.9	20	-50	14.6	14	
8-17-83-01		28.3	14.2	8	.1	13.2	-84	8.3	12	-27	16.3	18	5.2
-02		32.1		8	.09	16.6	-56	6.4	11	-43	12.1	17	
-03		24.5		6	.1	11.4	-90	7.6	15	-26	9.8	19	2.2
-04		24		6	.093	12	-80	8.0	14	-48	9.6	21	
8-18-83-01		32.4		10	.115	13.1	-63	7.5	14	-31	16.6	17	6.6
-02		26.9		10	.115	10.9	-18	7.6	21	-15	15.3	15	
9-6-83-01		25.5	16.3	10	.117	10.2	-10	7.5	18	12	14.9	15	
9-13-83-01	Single	20	23	8	.16	11.7	2	10.8	40				
-02		12.1	16	10	.11	10.7	2	9	19				
-03		14	17	8	.125	11	-27	8.8	15				

[a] N_c = anchor capacity/S_u x fluke area; for tandem tests, the average value of N_c is given.

Key to Measurements



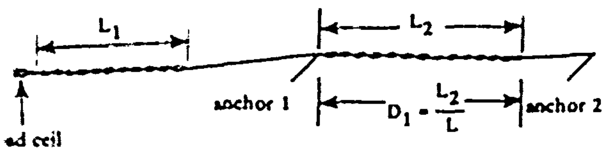
...r Model STATO Tests in Mud

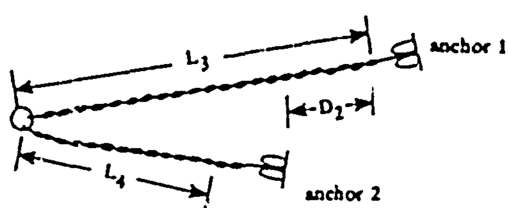
θ (deg)	Anchor 2 β (deg)	z (in.)	θ (deg)	Anchor Separation, D_1, (Fluke Lengths, L)	Mooring Line Characteristics: Anchor 1 L_1	Anchor 2 L_2
---					Wire (D)/27" - chain (A)	---
---					↓	---
14					Wire (D)/27" - chain (B)	---
14					↓	---
[illegible]					↓	---
[illegible]					↓	---
[illegible]					Wire (D)/27"	---
18					↓	---
---	[illegible]	19.75	22	6.6	↓	27" - wire (D)
[illegible]	-26	[illegible]	13	0.67	↓	27" - chain (B)
[illegible]	[illegible]	[illegible]	20	0.67	Wire (D)/27" - chain (B)	27" - chain (B)
17					Wire (D)/27" - chain (C)	
[illegible]					↓	---
[illegible]					↓	---
[illegible]	[illegible]	[illegible]	20	1.8	↓	7.4" - chain (B)
[illegible]	[illegible]	[illegible]	25		↓	↓
[illegible]	[illegible]	[illegible]	-3	2.2	↓	9" - chain (B)
[illegible]	[illegible]	[illegible]	22	3.9	↓	↓
[illegible]	[illegible]	[illegible]	19		↓	↓
[illegible]	-36	15.1	16	5.2	↓	21" - chain (B)
[illegible]	[illegible]	16.5	15		↓	↓
16	[illegible]	[illegible]	20	8.1	↓	33" - chain (B)
[illegible]	-31	[illegible]	16		↓	↓
15	-36	15.1	16		↓	33" - chain (A)
[illegible]	[illegible]	[illegible]	14		↓	↓
[illegible]	[illegible]	[illegible]	18	5.2	↓	21" - chain (A)
[illegible]	[illegible]	12.1	17		↓	↓
[illegible]	-26	[illegible]	19	2.2	↓	16" - chain (A)
14	-48	[illegible]	21		↓	↓
14	-41	16.0	17	6.6	↓	27" - wire (D)
[illegible]	-15	15.3	15		↓	↓
[illegible]	12	14.9	15		↓	↓
[illegible]					↓	---
[illegible]					↓	---
[illegible]					↓	

[illegible]

Mooring Line	Equivalent Diameter (in.)	Prot...
A - Small chain [27 in.]*	0.384	2-1/4-i...
B - Large chain [27 in.]*	0.626	3-1/2-i...
C - Large chain doubled [27 in.]*	0.946	5-1/2-i...
D - Wire	0.094	1-7/8-i...

*Equivalent to 1/2 shot chain.





Mooring Line Characteristics	
Anchor 1 L_1	Anchor 2 L_2
Wire (D)/27" - chain (A)	---
↓	---
Wire (D)/27" - chain (B)	---
↓	---

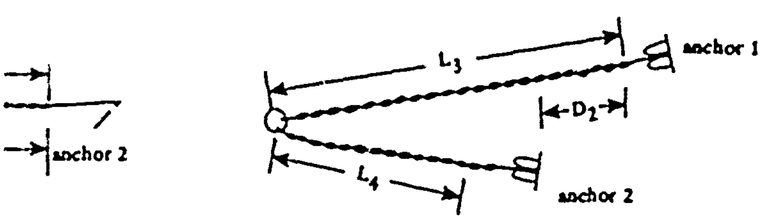
Wire (D)/27"	---
↓	---
	27" - wire (D)
	27" - chain (B)
Wire (D)/27" - chain (B)	27" - chain (B)
Wire (D)/27" - chain (C)	
↓	---

	7.4" - chain (B)
	↓
	9" - chain (B)
	↓
	21" - chain (B)
	↓
	33" - chain (B)
	↓
	33" - chain (A)
	↓
	21" - chain (A)
	↓
	16" - chain (A)
	↓
	27" - wire (D)
	↓

↓	---

Mooring Line	Equivalent Diameter (in.)	Prototype
A - Small chain [27 in.]*	0.384	2-1/4-in. chain
B - Large chain [27 in.]*	0.626	3-1/2-in. chain
C - Large chain doubled [27 in.]*	0.946	5-1/2-in. chain
D - Wire	0.094	1-7/8-in. wire

*Equivalent to 1/2 shot chain.



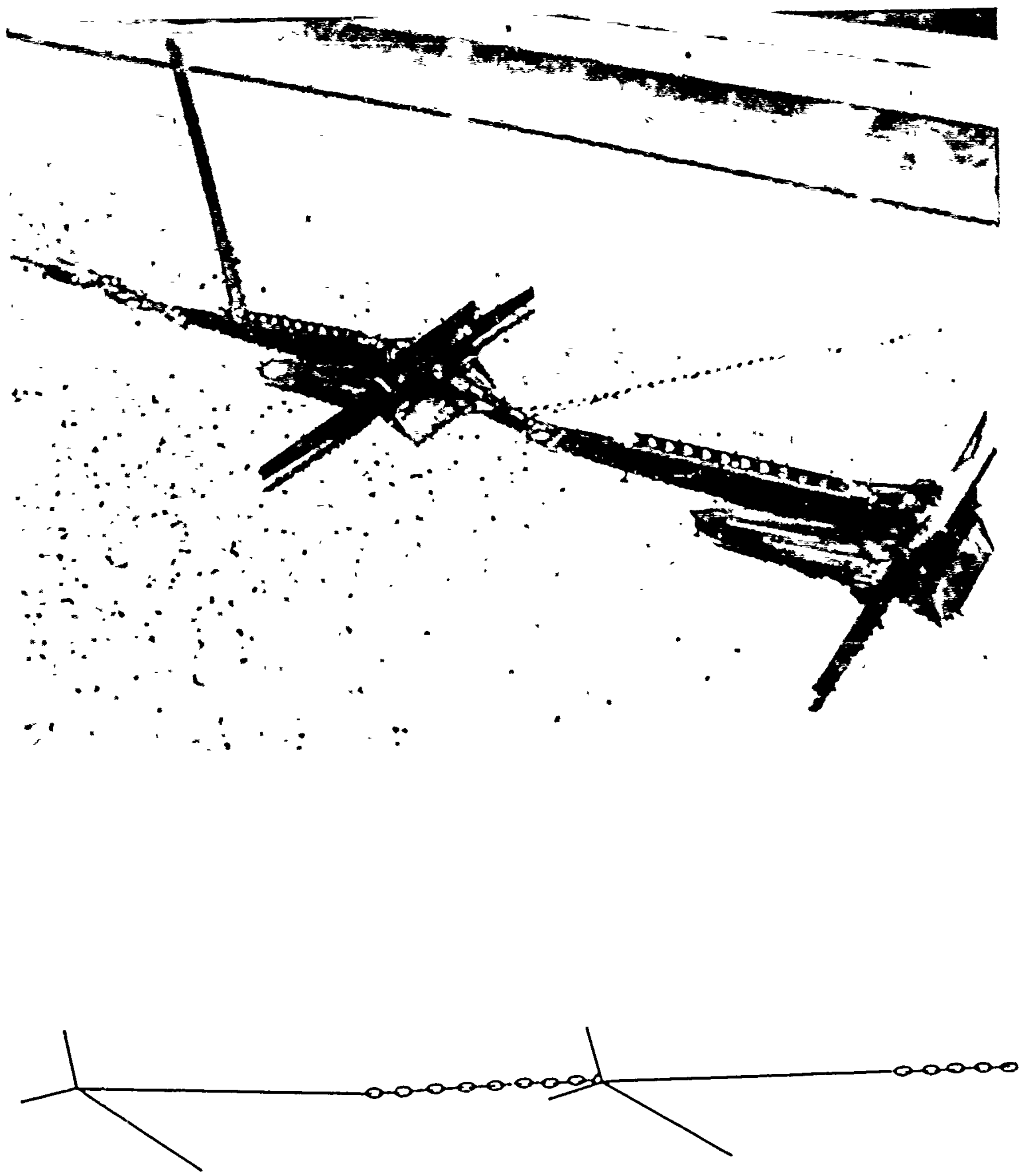
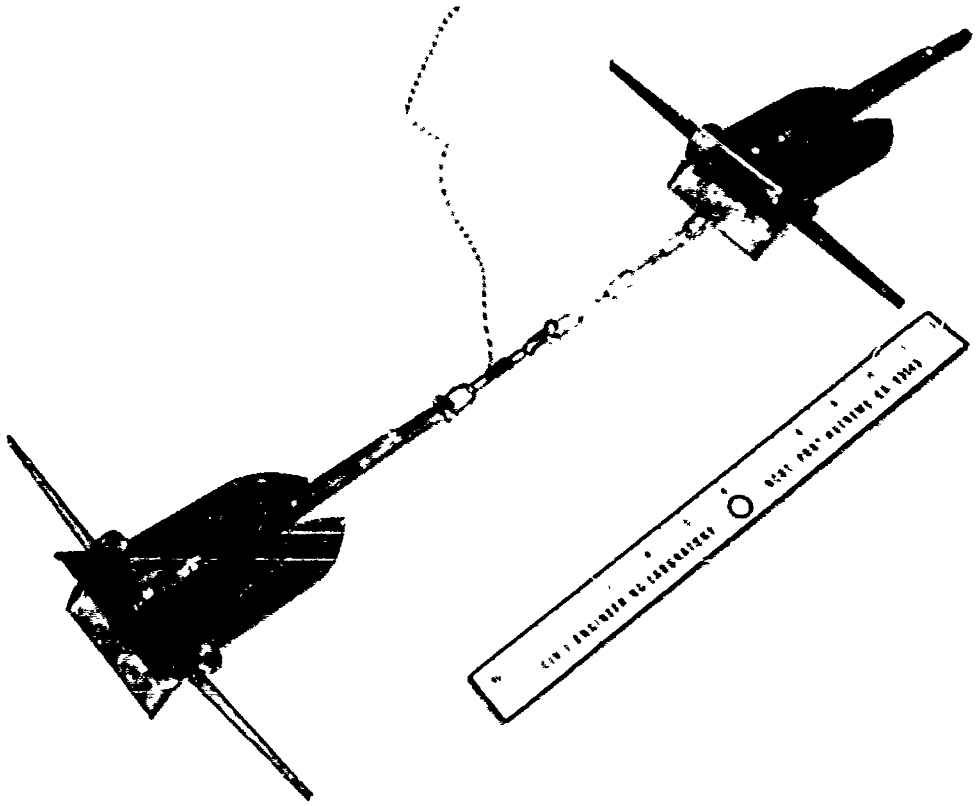


Figure 1. Tandem anchors - crown to shackle rigging method.



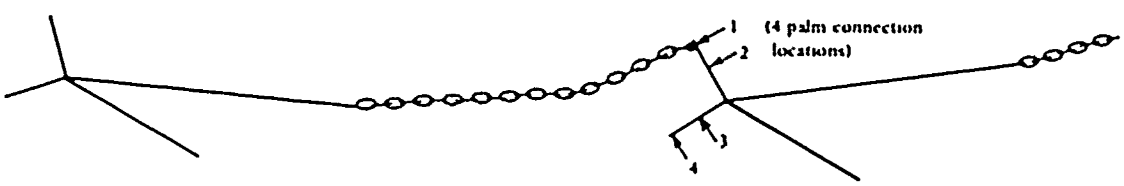


Figure 2. Tandem anchors - palm to shackle rigging method.

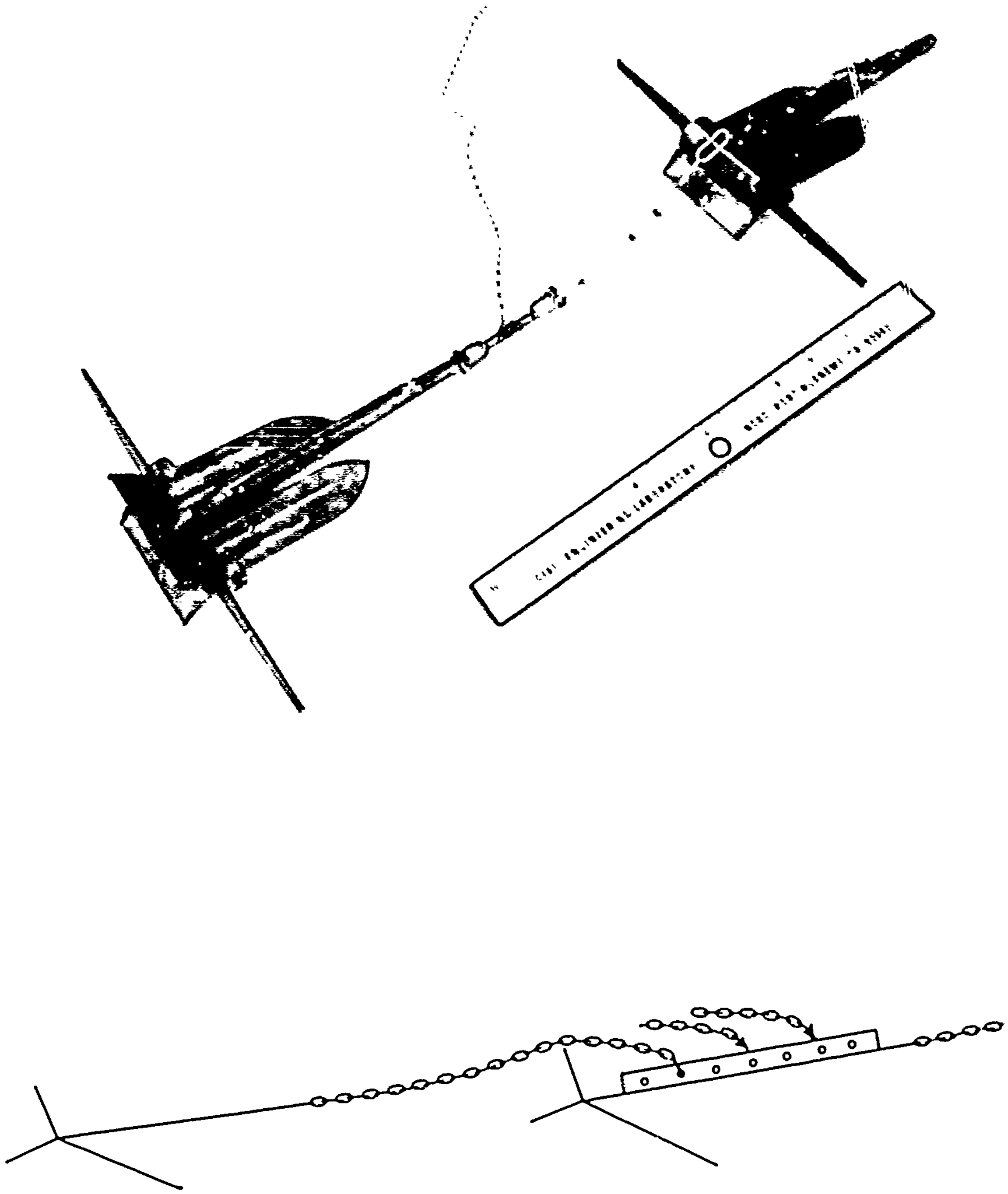
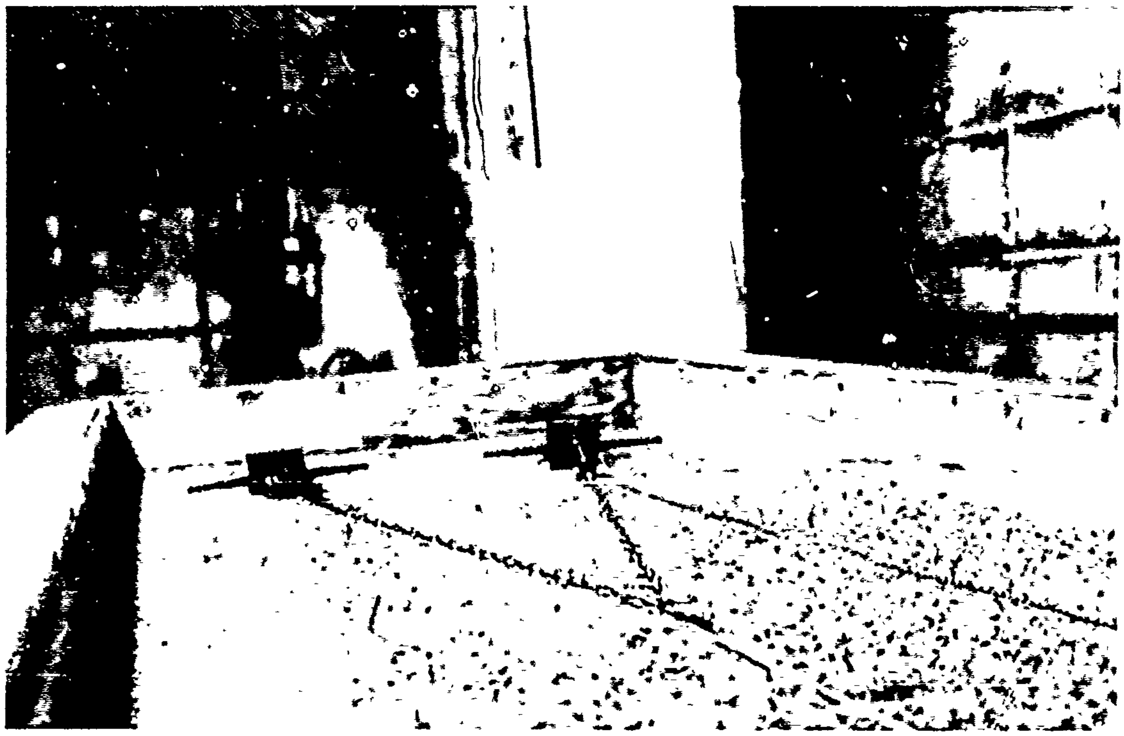
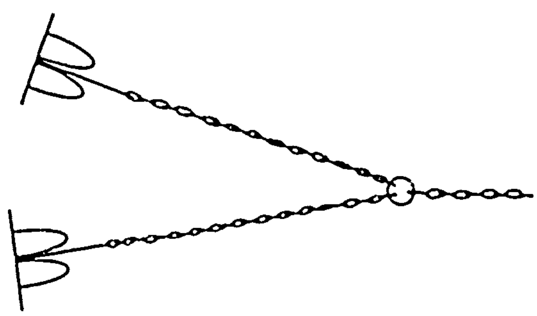
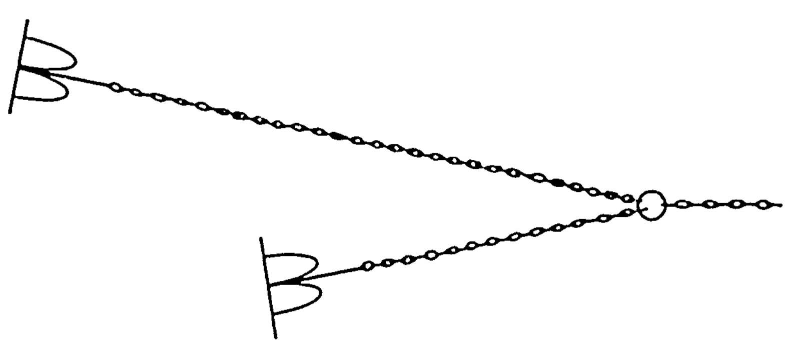


Figure 3. Tandem anchors - shank to shackle rigging method.





(a) Side by side.



(b) Staggered.

Figure 4. Parallel anchor rigging methods.

(a) 200-lb STATO anchor.

(b) 350-lb DANFORTH anchor.

Figure 5. Anchors used during small-scale field tests in sand.

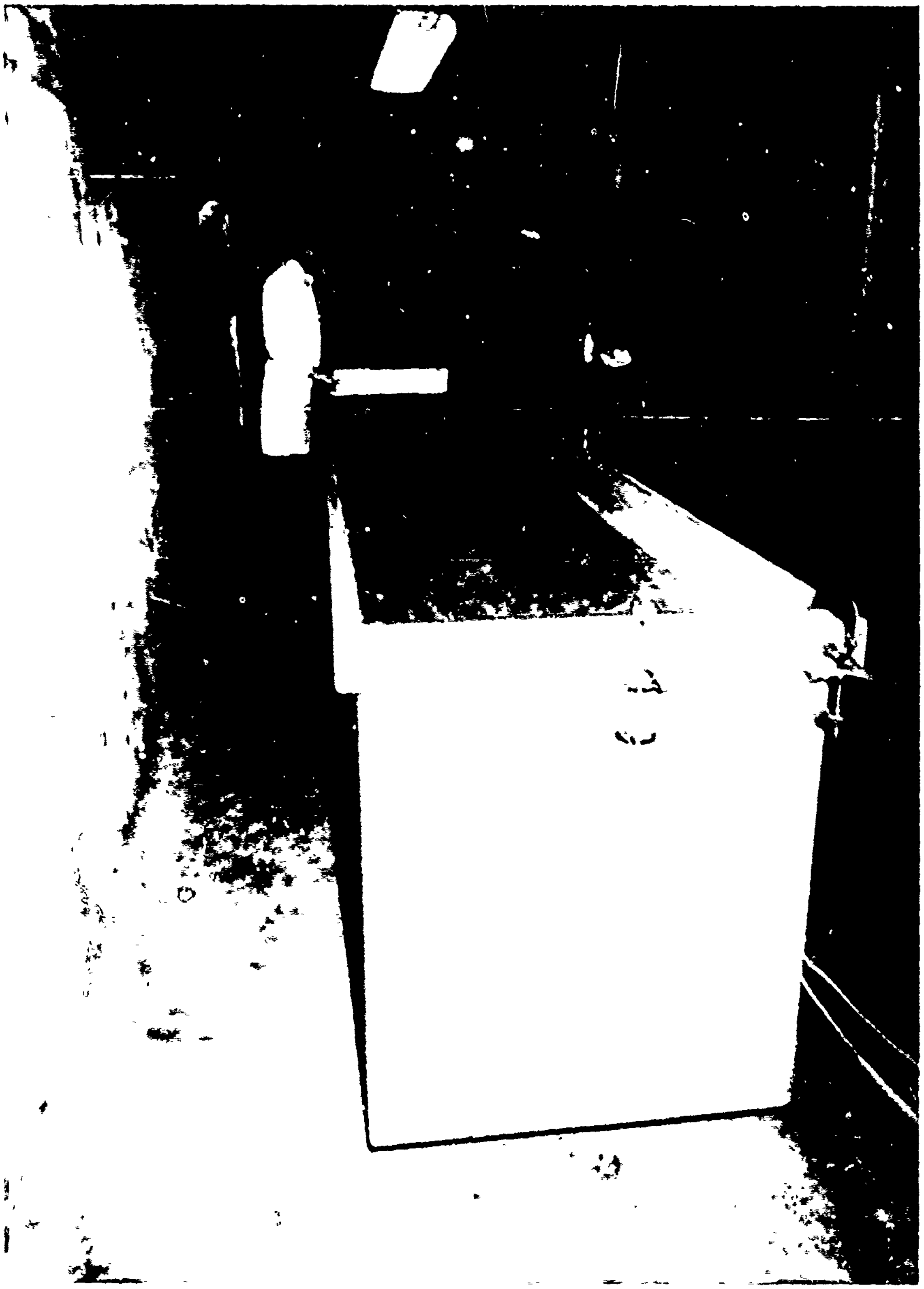


Figure 6. Mud test box - 16 by 2.5 by 2.5 ft.

Depth (in.)	Shear Strength (psi) for Horizontal Distance of Anchor Travel in Tank (ft)--								
	0	1	2	3	4	6	8	10	12
3	0.09	0.11	0.09	0.10					
6	0.10	0.10	0.10	0.09	0.09	0.09	0.10		
9	0.10	0.09	0.09	0.10	0.09	0.10	0.10	0.11	0.10
12			0.10	0.08	0.10	0.10	0.10	0.11	0.10
15						0.10	0.10	0.11	0.12
18							0.11	0.12	0.12

Figure 7. Typical test tank shear strength profile C (Test No. 08-16-83-02).

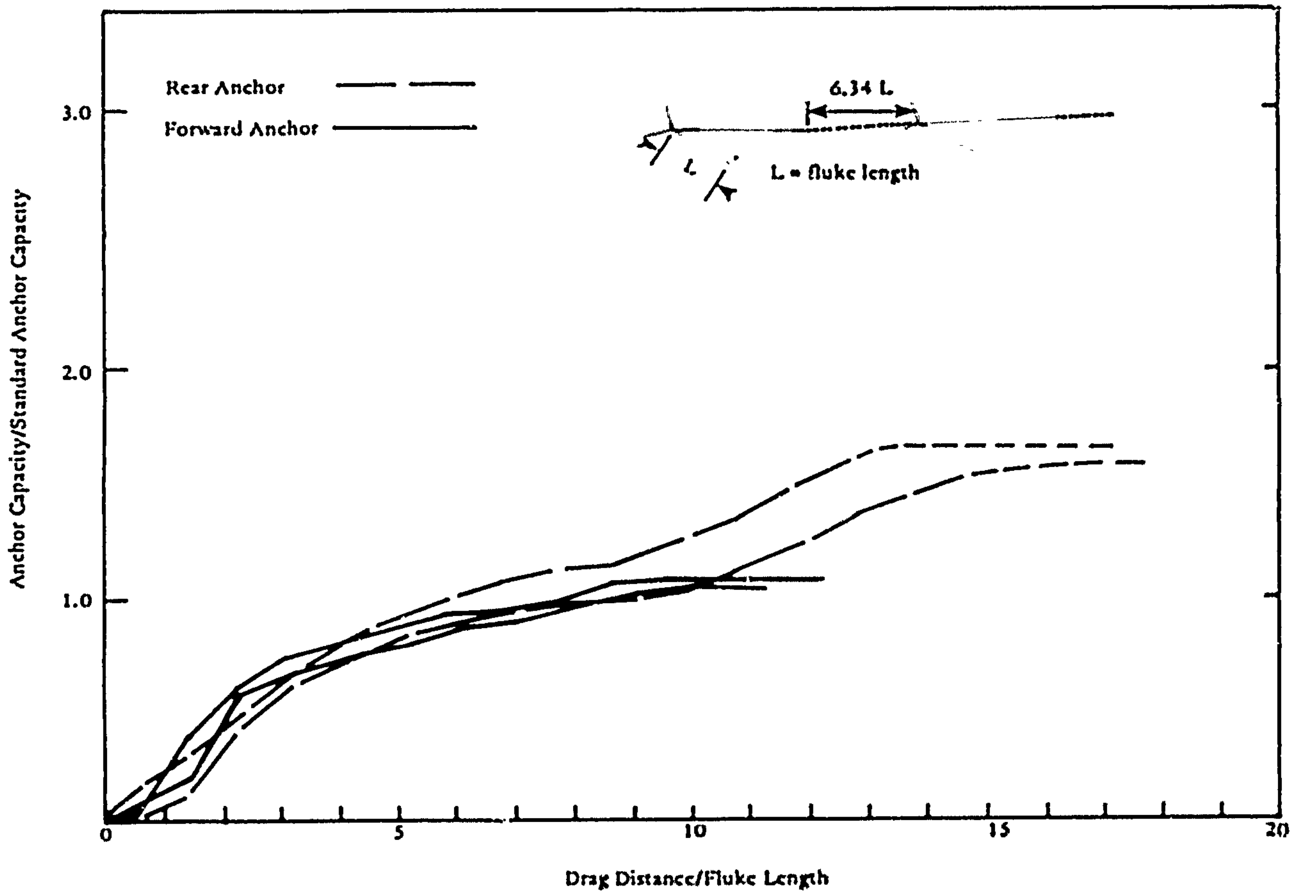


Figure 8. Typical crown-shackle tandem anchor capacity in dry sand.

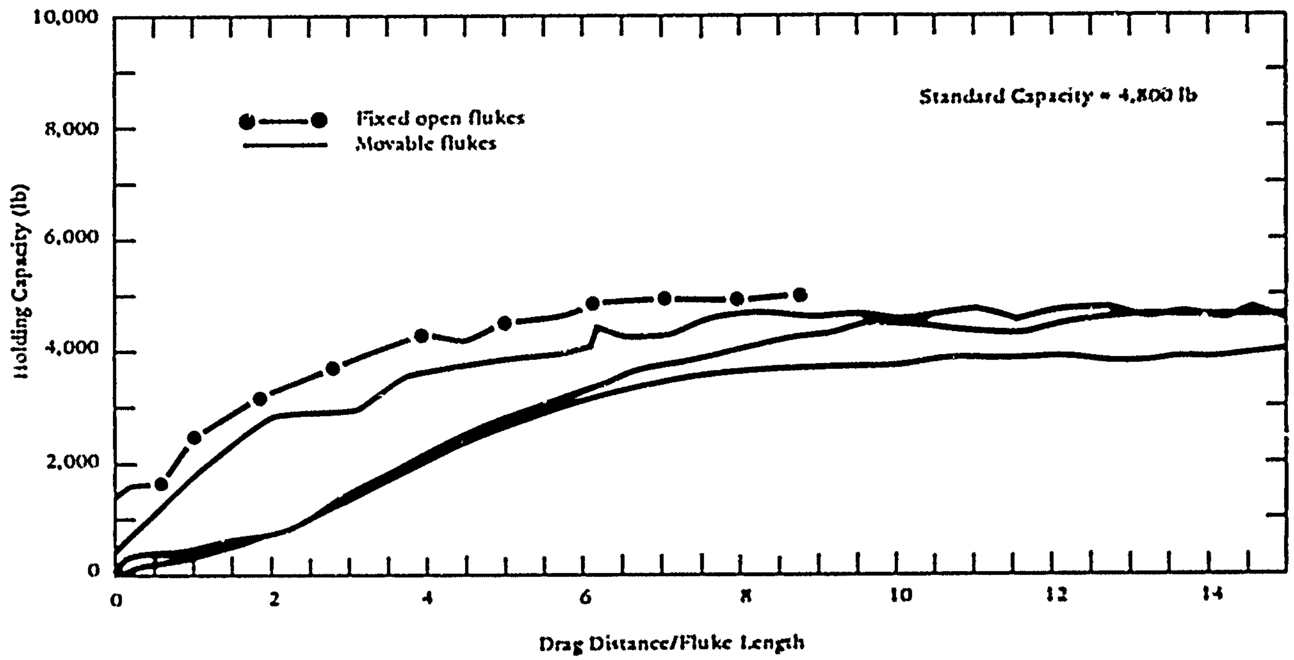


Figure 16. Anchor plus chain load versus drag distance for 200-lb STATO anchor in sand.

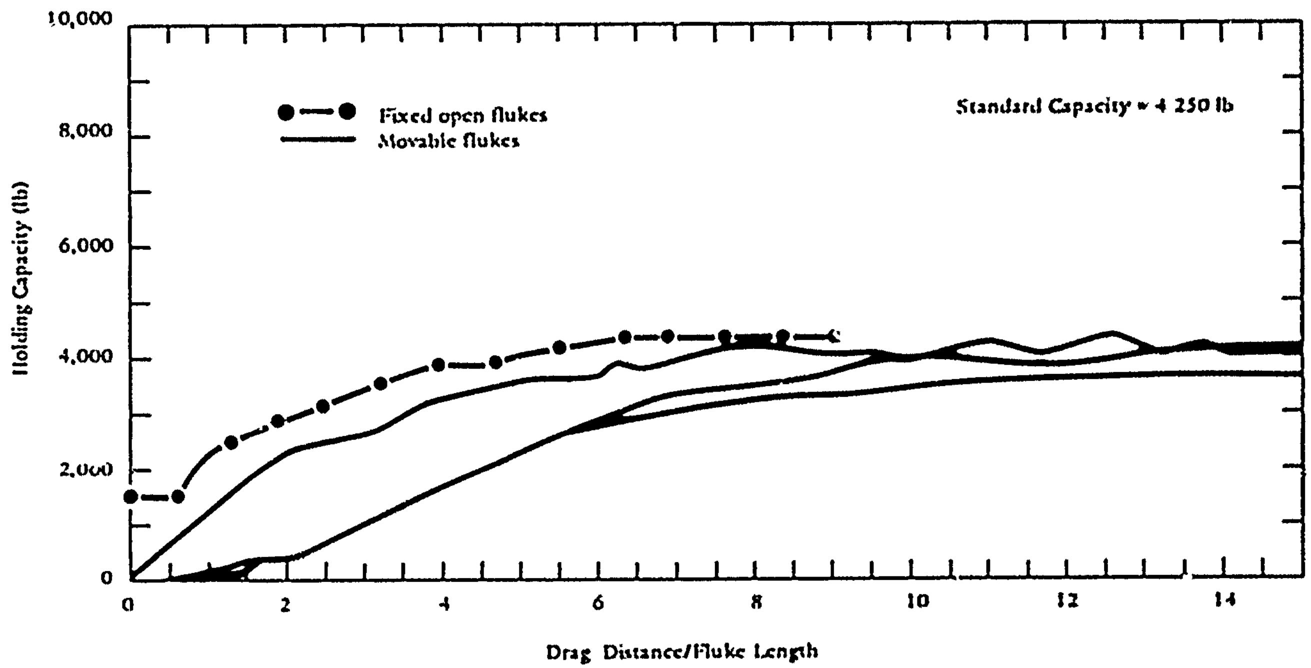


Figure 15. Anchor load versus drag distance for 200-lb STATO with chain in sand.

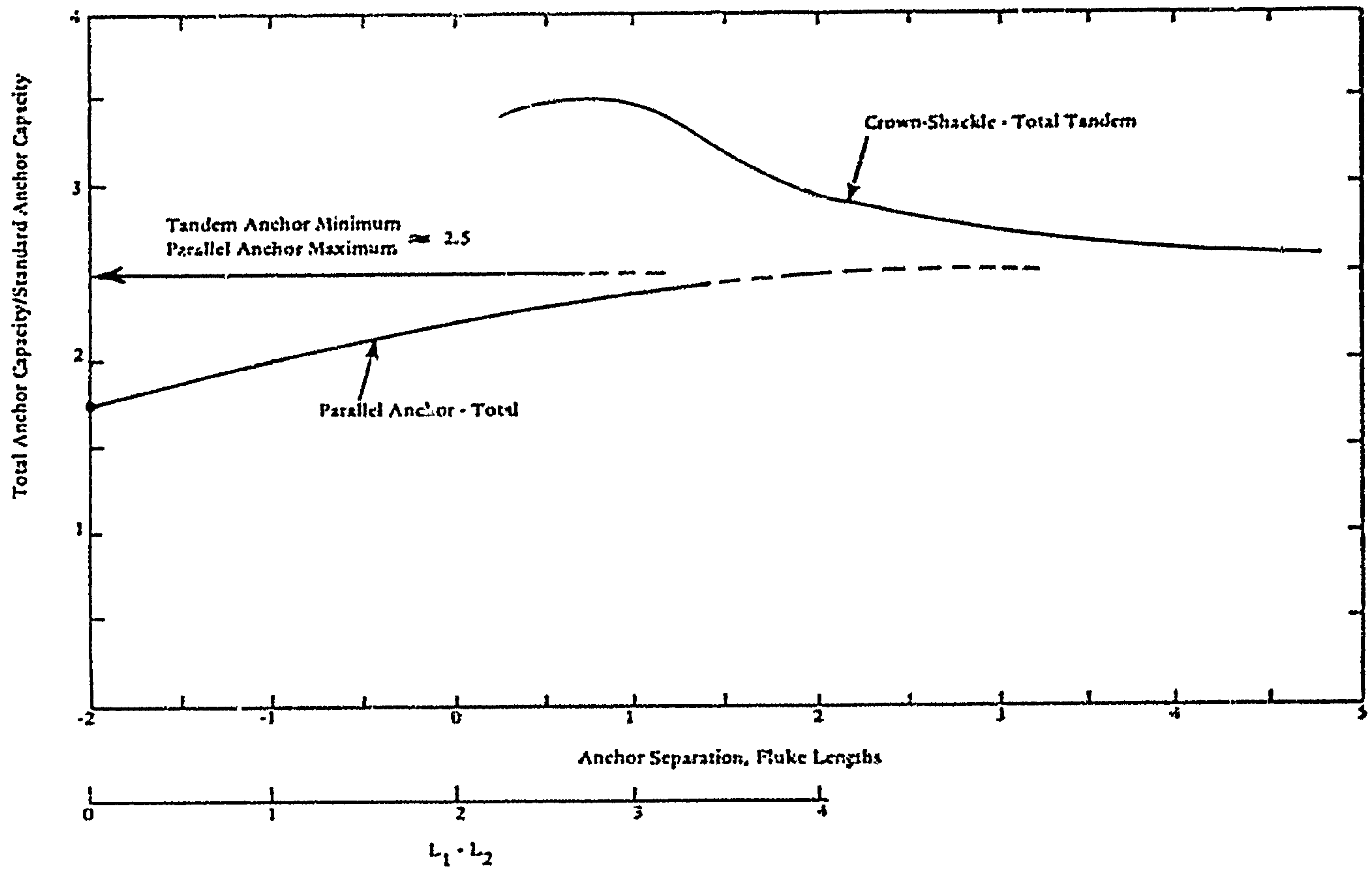


Figure 14. Comparison between tandem and parallel anchor (ground ring-shackle) performance in sand.

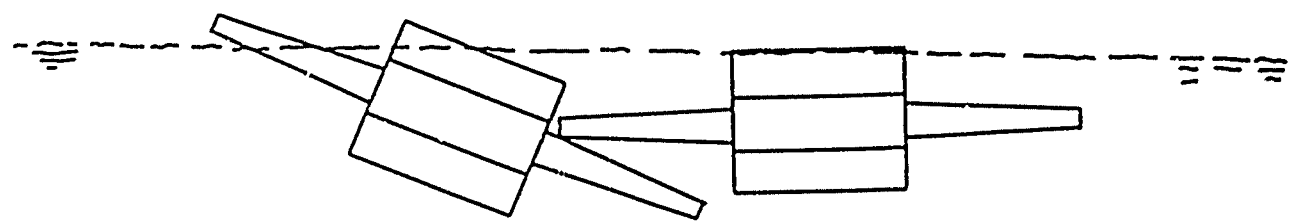


Figure 13. Anchor interference in ground ring-shackle arrangement in sand; anchors side by side, $L_1 - L_2 = 0$ (Refer to Figure 12).

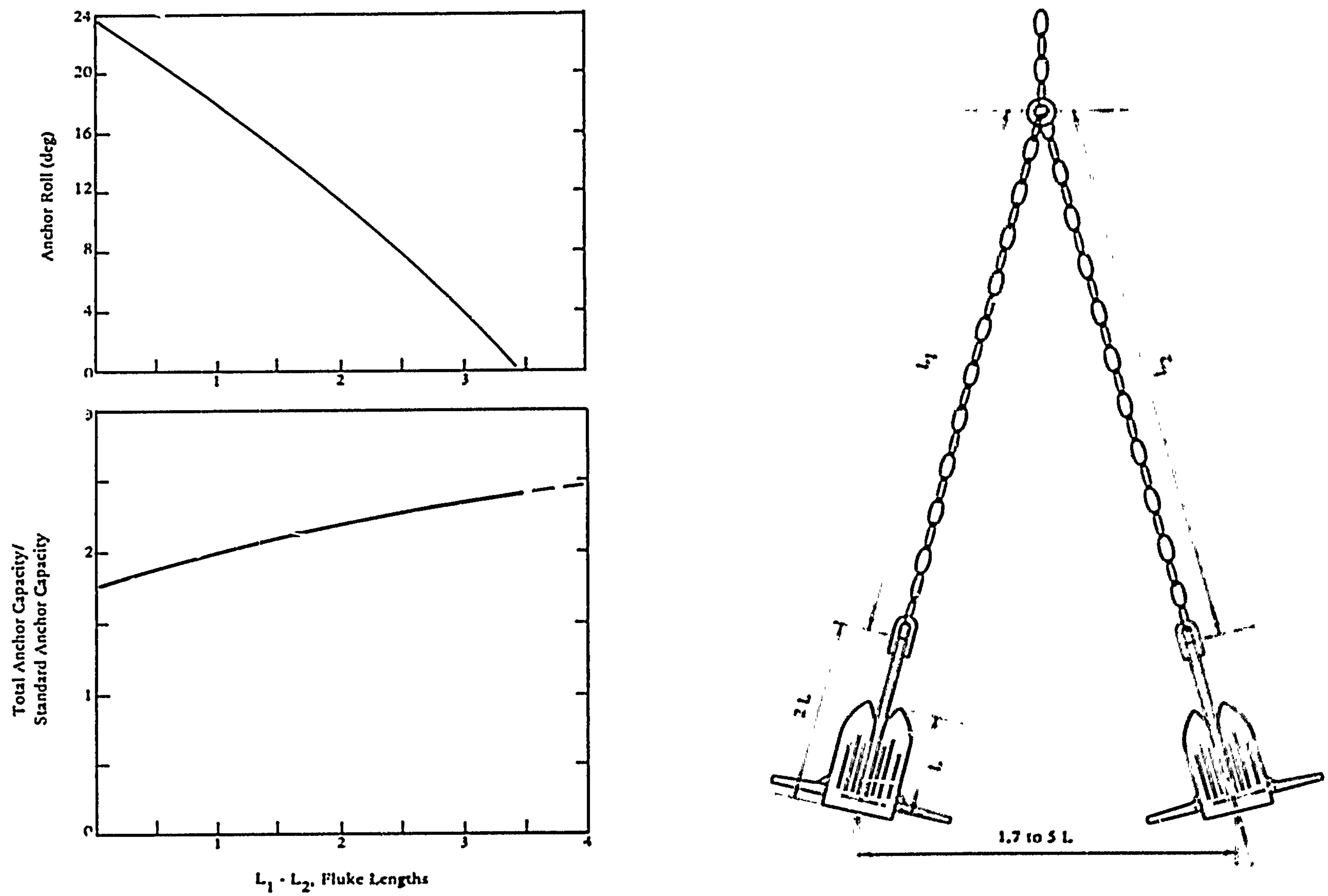


Figure 12. Ground ring to shackle rigging method performance data.

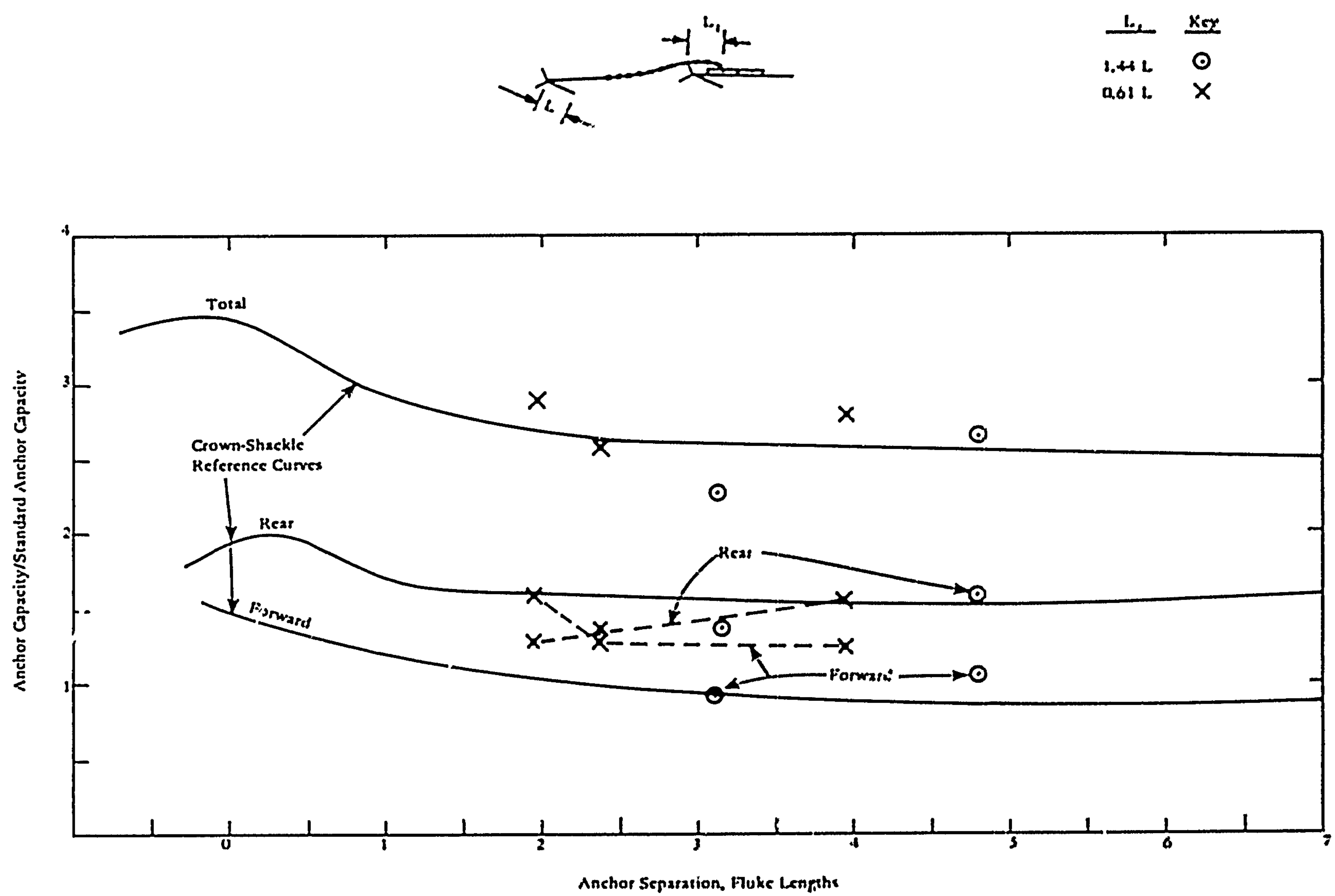


Figure 11. Summary shank-to-shackle tandem anchor data in sand.

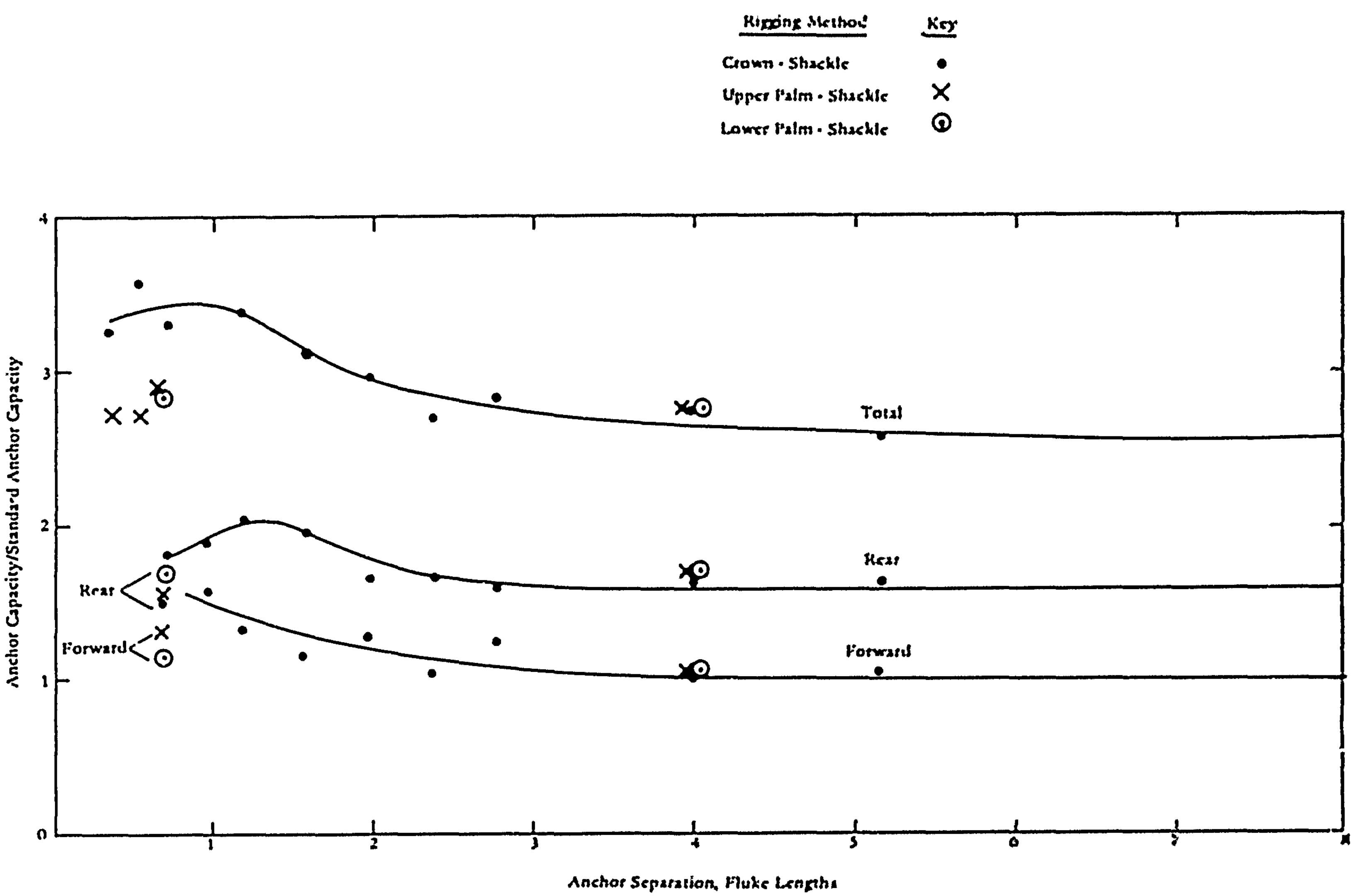


Figure 10. Tandem anchor capacity relative to anchor spacing in sand.

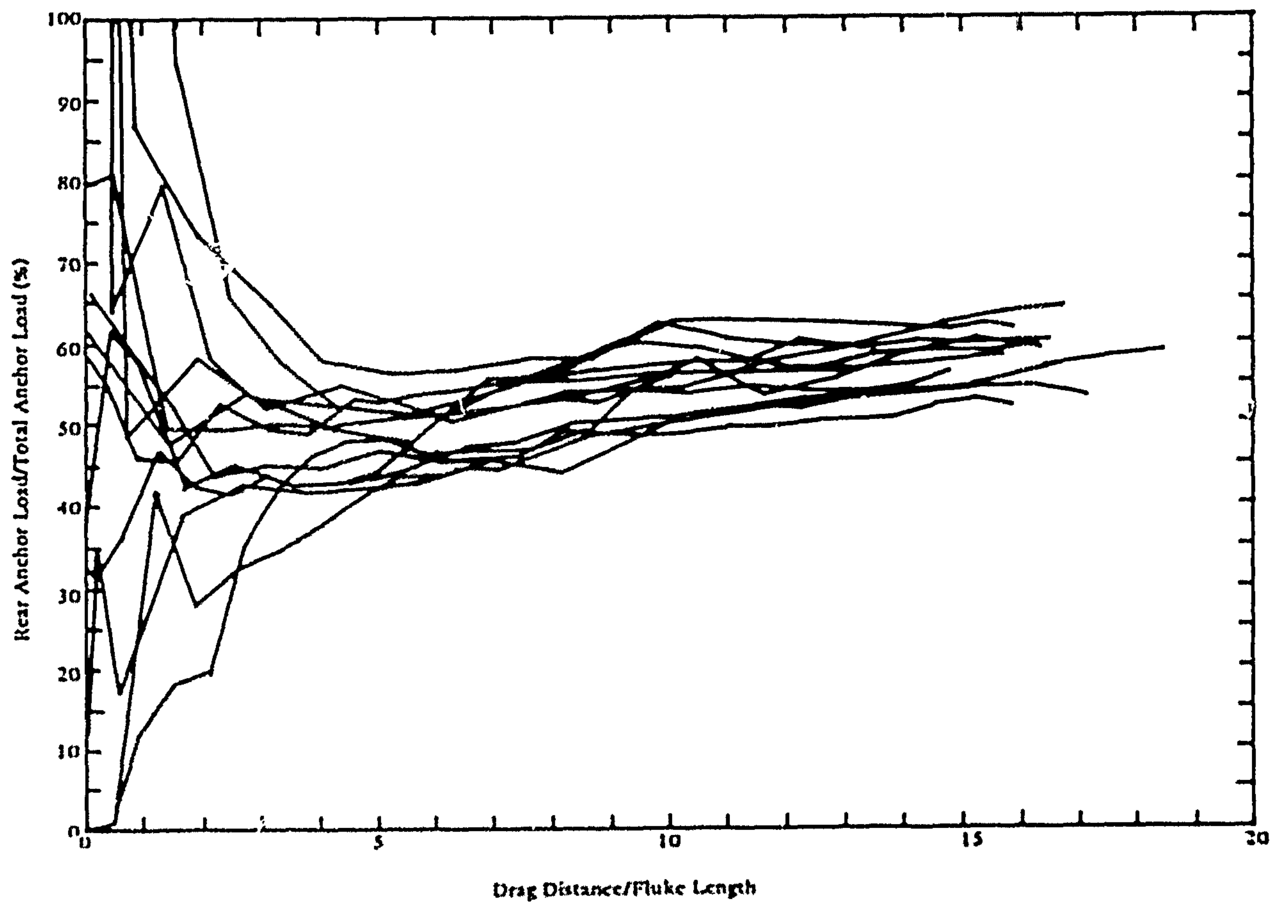


Figure 9. Rear anchor contribution to total load for crown-shackle arrangement in dry sand.

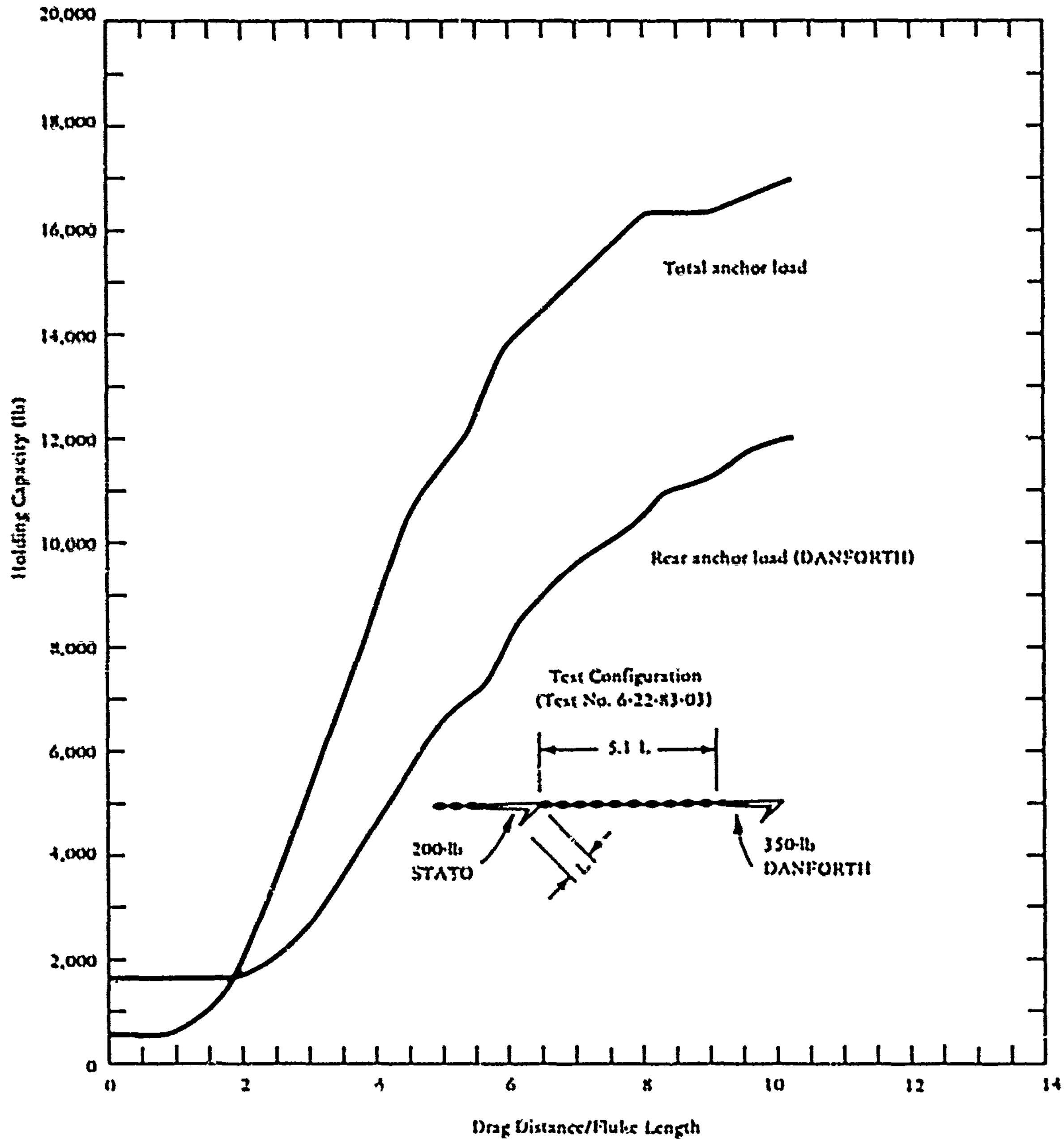


Figure 24. Holding capacity versus drag distance - STATO with DANFORTH as tandem anchor.

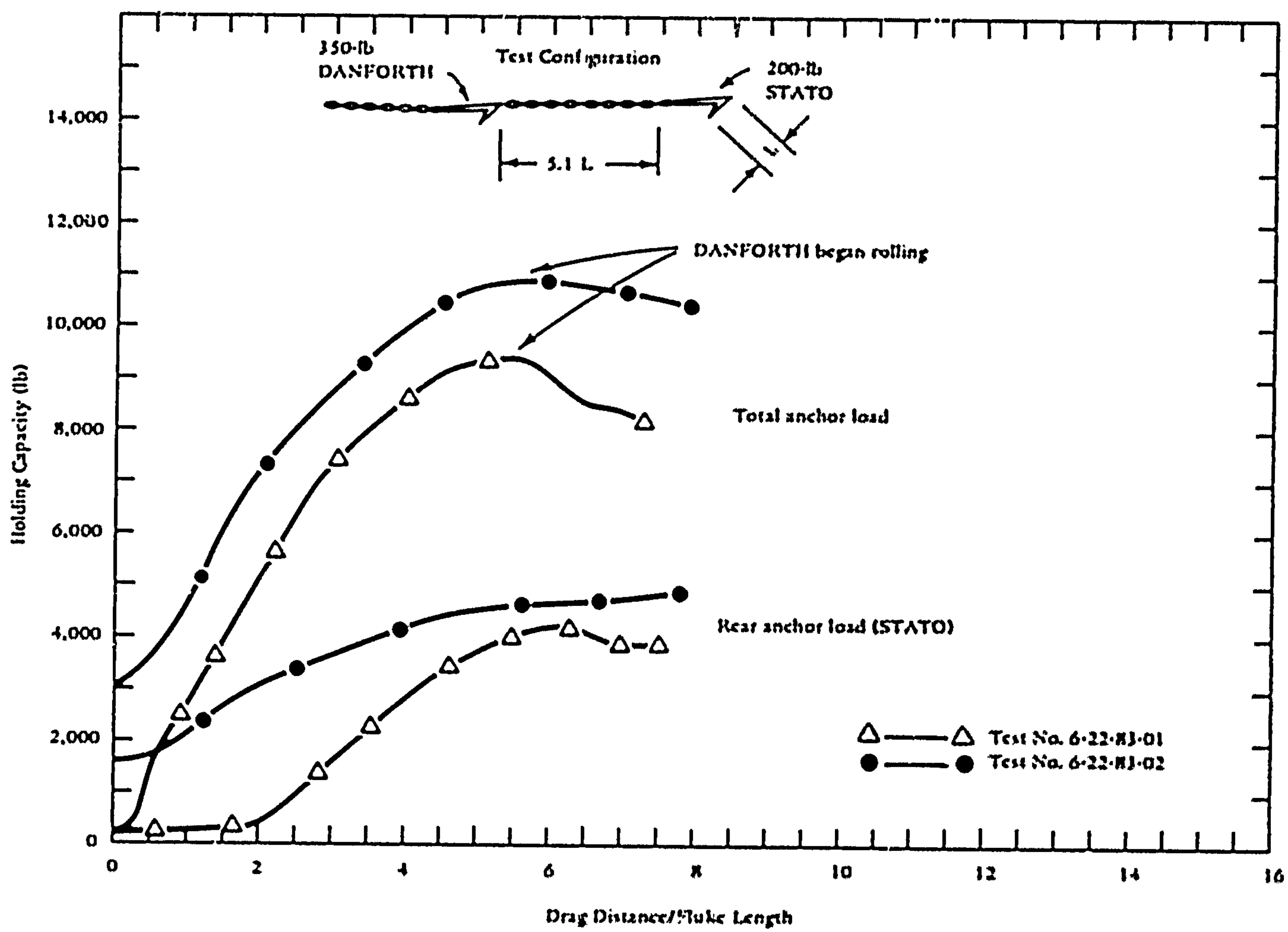


Figure 23. Holding capacity versus drag distance - DANFORTH with STATO as tandem anchor.

(a) STATO as piggyback anchor.

(b) DANFORTH as piggyback anchor.

Figure 22. DANFORTH and STATO anchors used in tandem combinations.

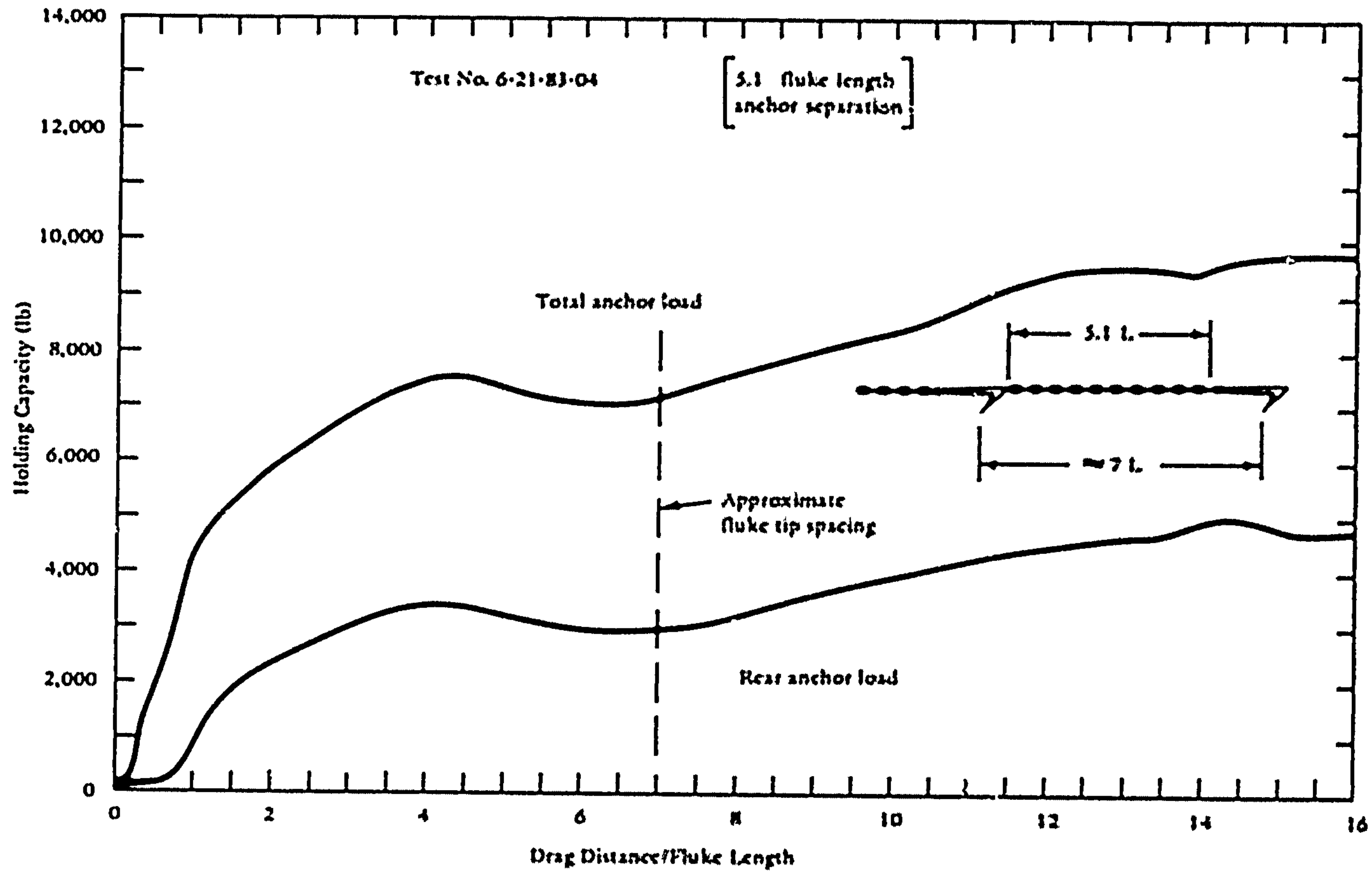


Figure 21. Holding capacity versus drag distance for 200-lb STATO anchors in tandem in sand.

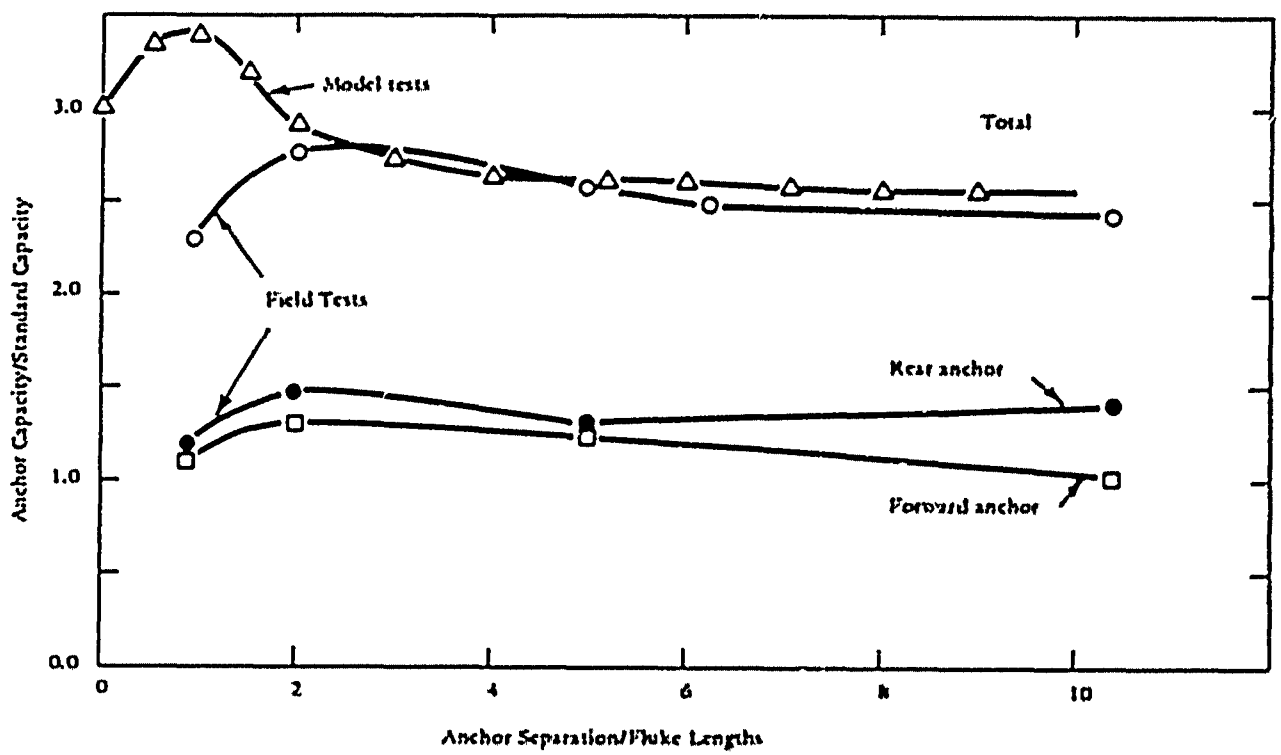


Figure 20. Summary shank to shackle tandem data for 200-lb STATO anchors in sand.

Figure 19. Tandem STATO anchors at two fluke length spacing. STATO's have flukes fixed open.

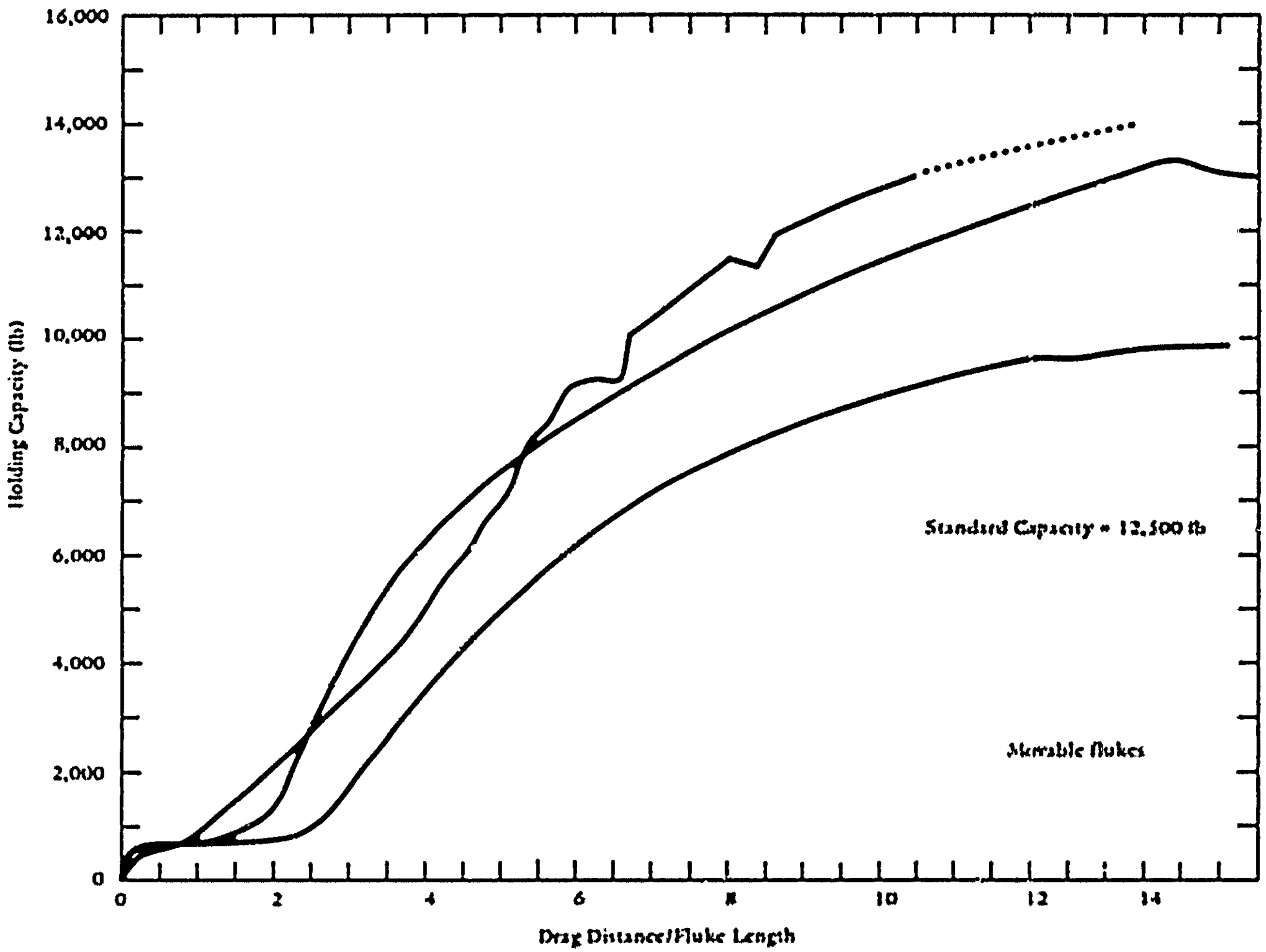


Figure 18. Anchor load versus drag distance for 350-lb DANFORTH with chain in sand.

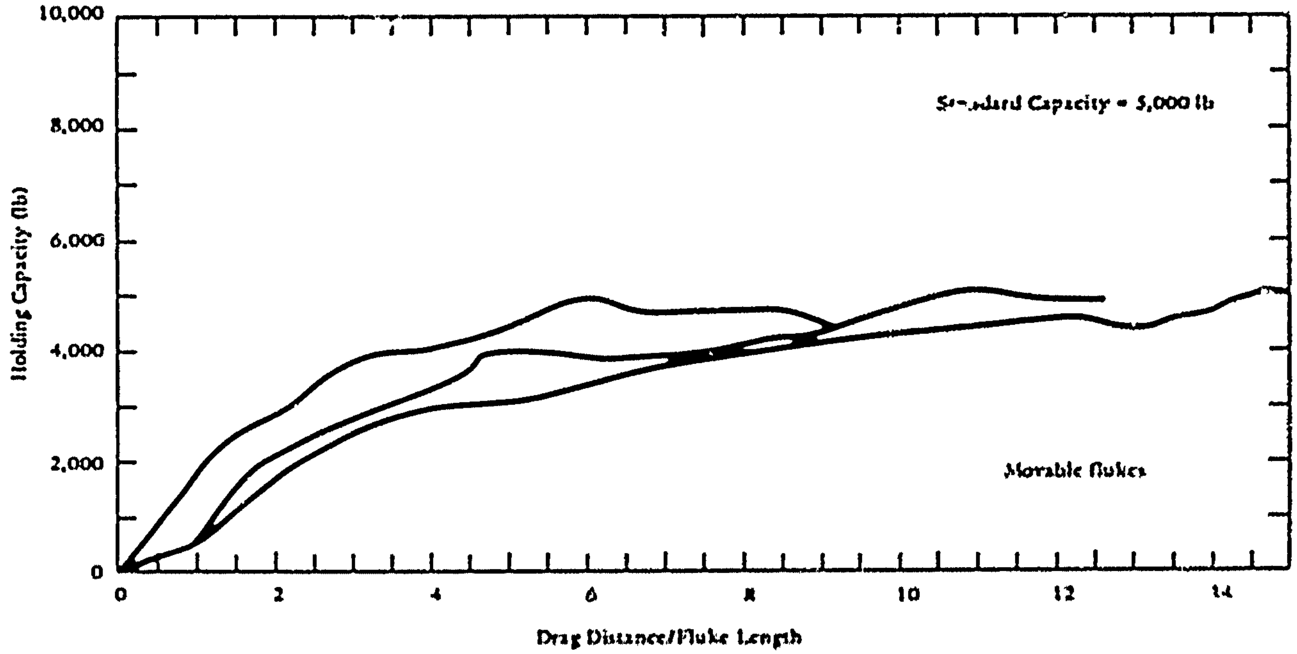


Figure 17. Anchor load versus drag distance for 200-lb STATO with wire in sand.

Figure 25. Tandem DANFORTH-STATO combination with a STATO in rear showing rolled DANFORTH.

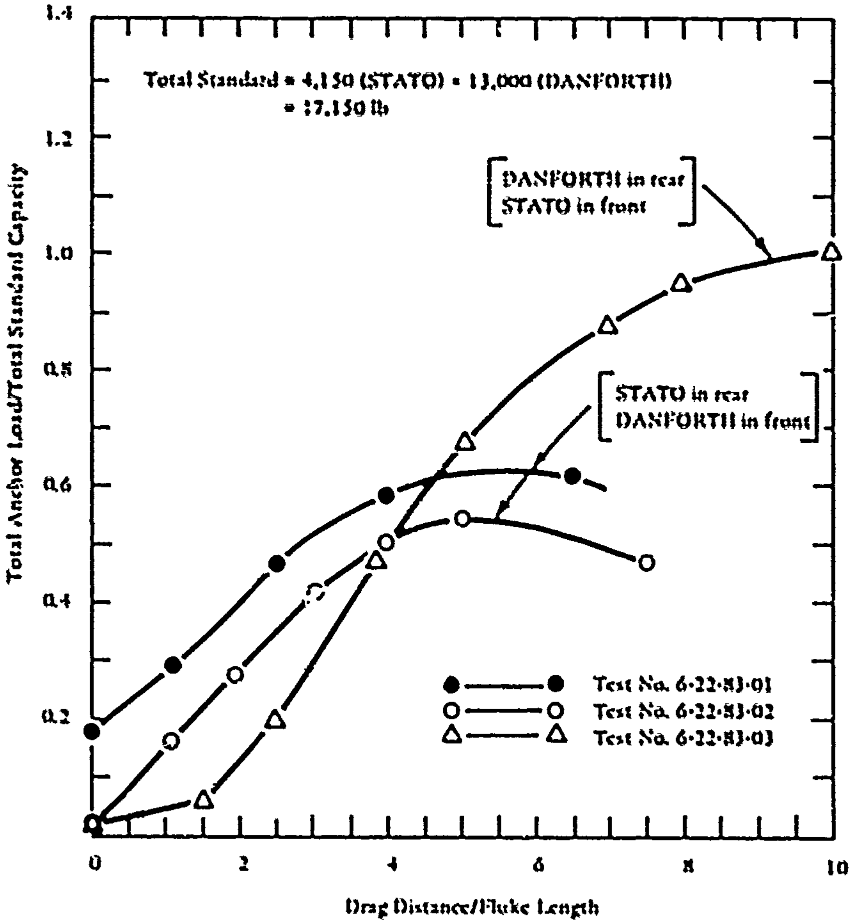


Figure 26. Summary tandem data for DANFORTH and STATO anchor combination.

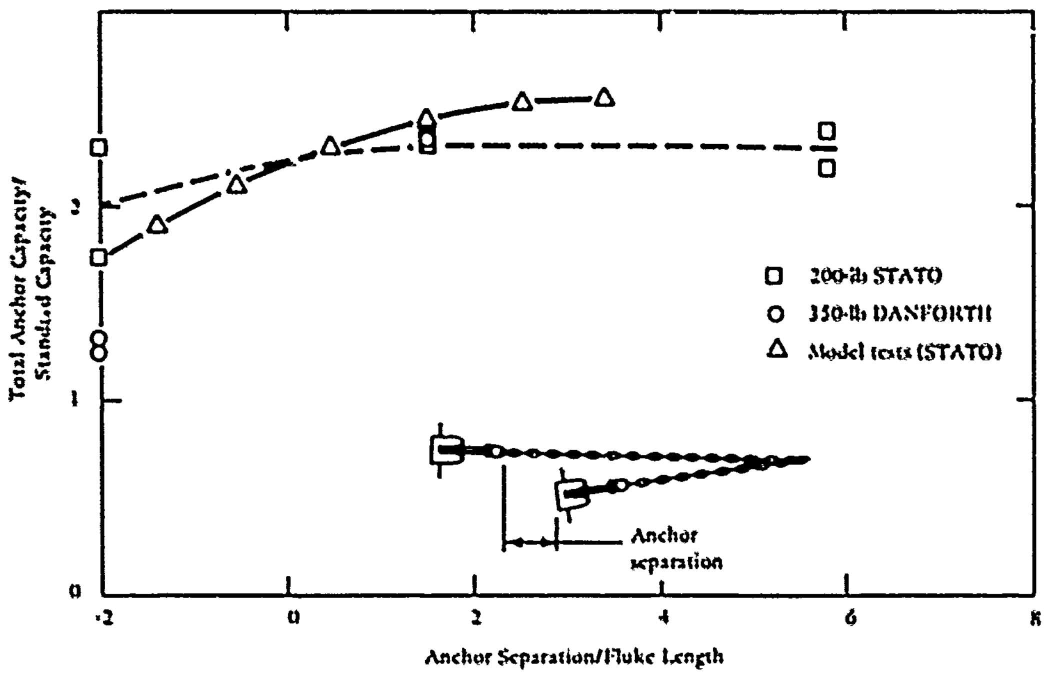


Figure 27. Summary parallel anchor data from beach test.

(a) Parallel STATO anchors.

(b) Parallel DANFORTH anchors.

Figure 28. Parallel anchors - side by side - illustrating anchor interference during drag.

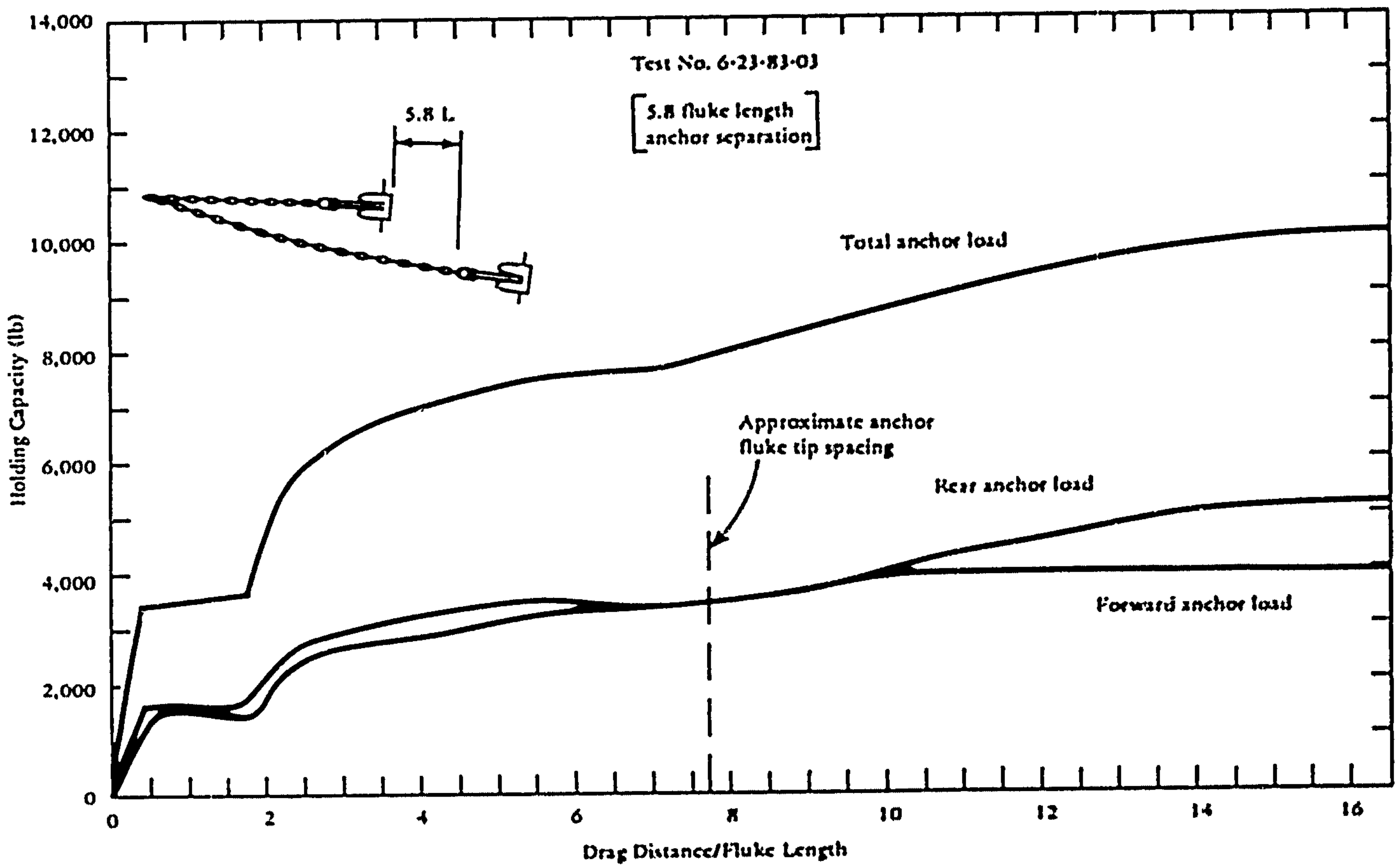


Figure 29. Holding capacity versus drag distance from 200-lb STATO anchors in parallel in sand.

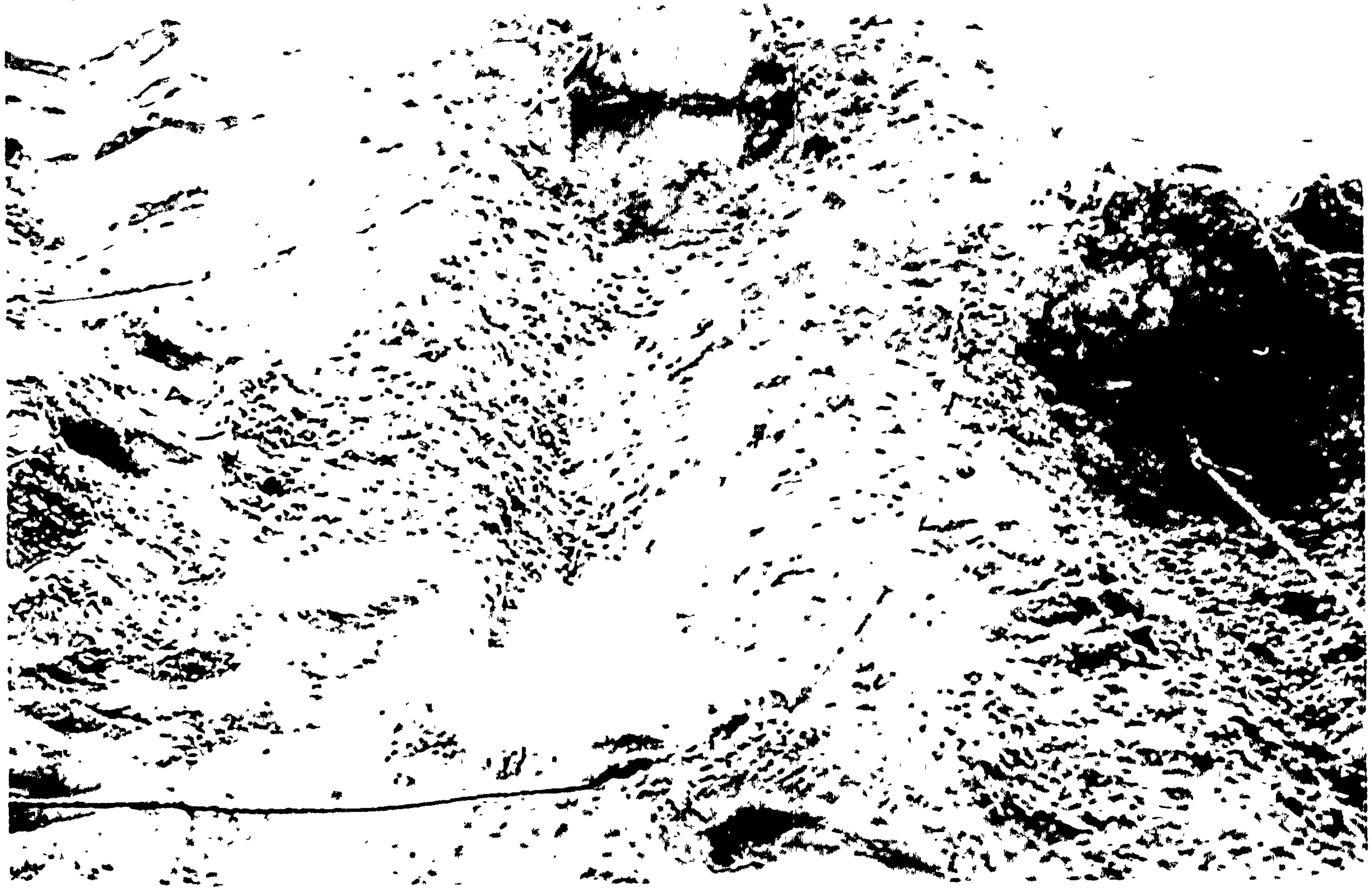


Figure 30. Parallel anchors - staggered - illustrating rear anchor rolling into trough created by forward anchor.

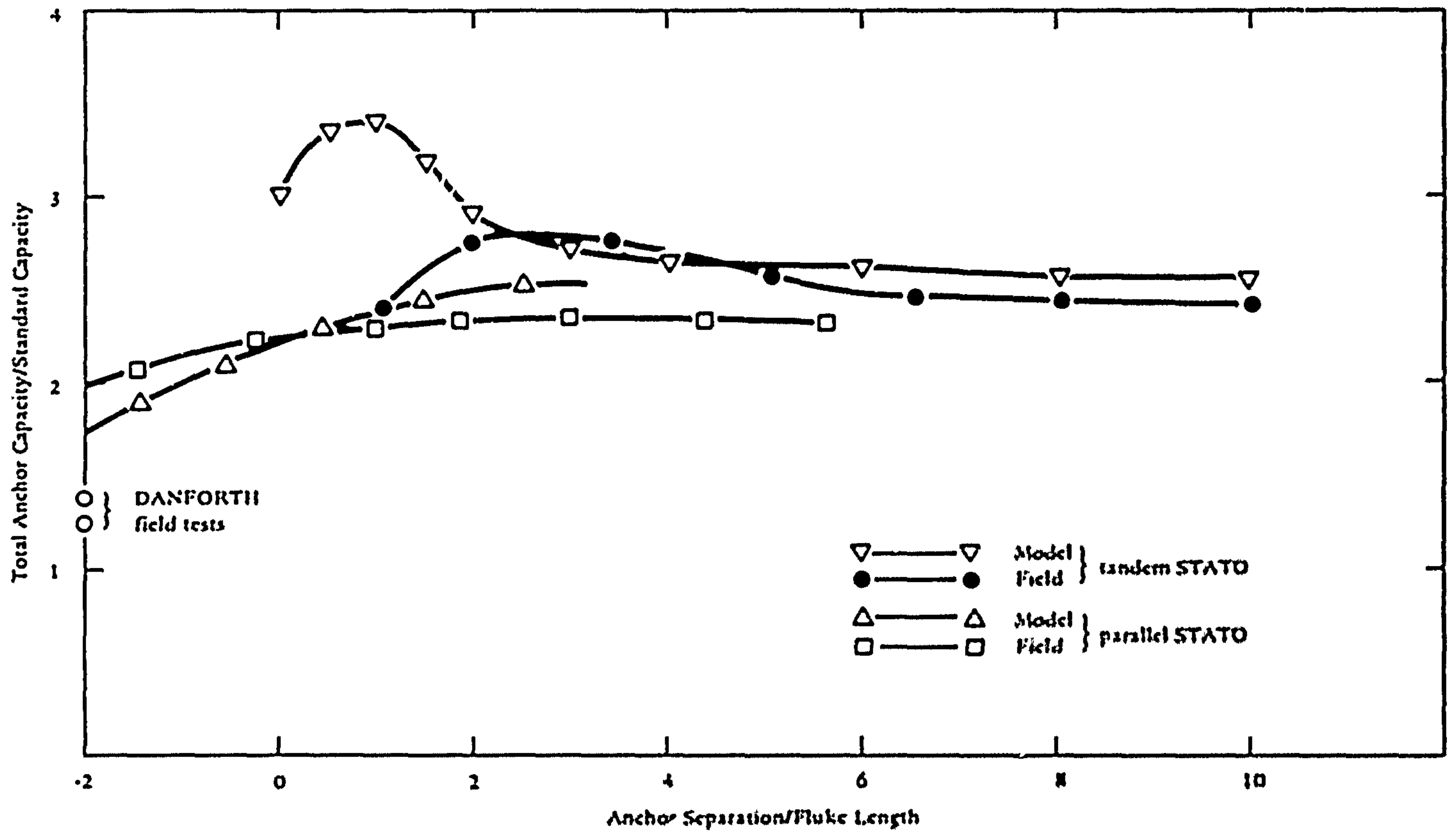
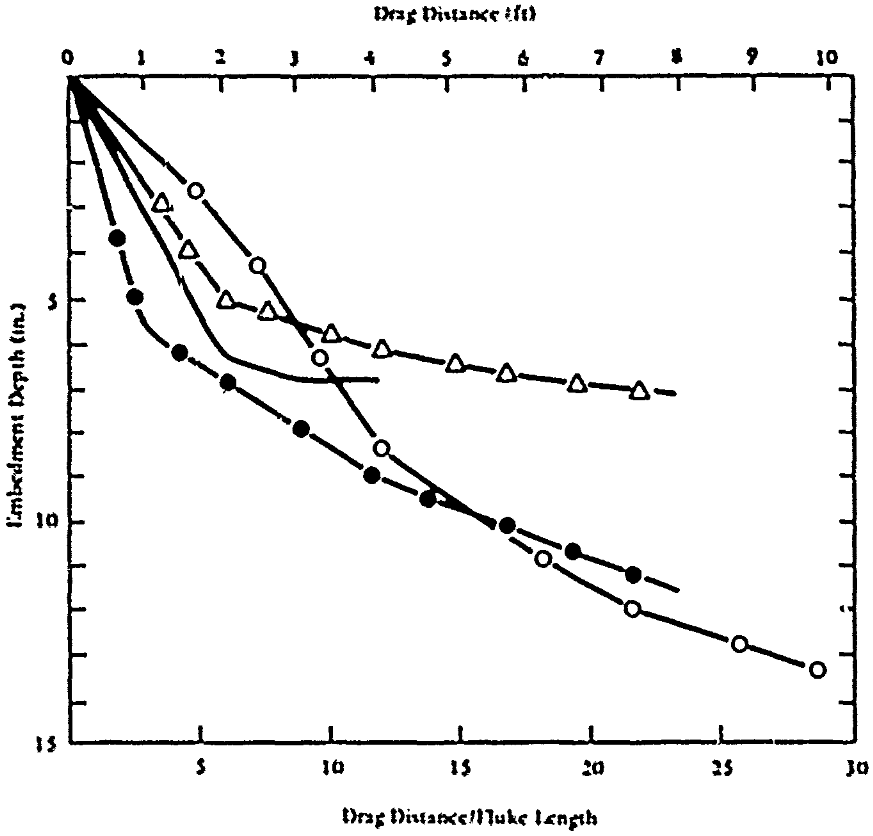


Figure 31. Field and model test data comparison.



Test	Link	Equivalent Diameter (in.)	Prototype
8-9-83-02 ○———○	Small chain [27 in.]*	0.384	2-1/4-in. chain
8-10-83-03 △———△	Large chain [27 in.]*	0.626	3-1/2-in. chain
8-10-83-05 ○———○	Wire	0.094	1-7/8-in. wire
8-11-83-05 ———	Large chain doubled [27 in.]*	0.946	5-1/2-in. chain

*Equivalent to 1/2 shot chain.

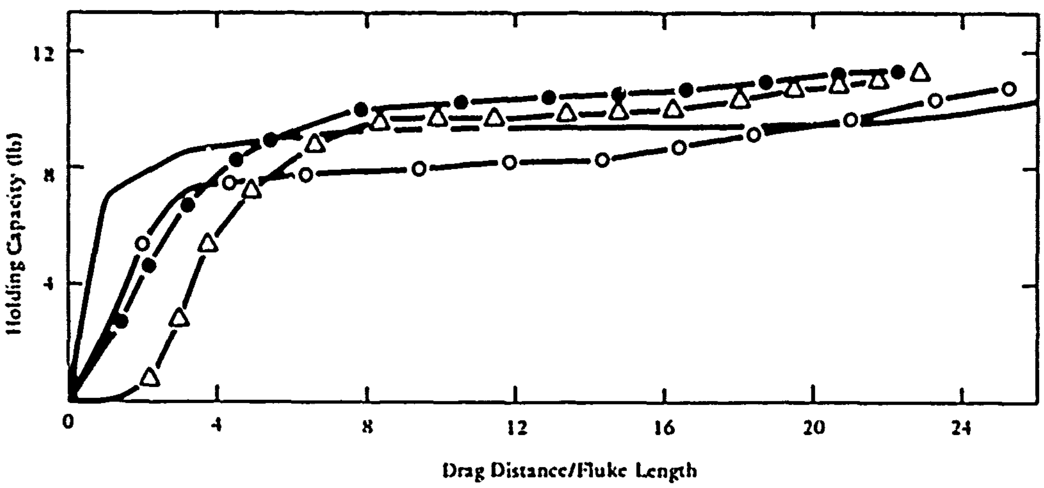


Figure 32. Performance of single STATO anchors with different mooring lines in similar strength mud.

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UCT ONE OIC, Norfolk, VA
UCT TWO OIC, Port Hueneme CA
US DEPT OF INTERIOR Bur of Land Mgmnt Code 583, Washington DC
US GEOLOGICAL SURVEY Off Marine Geology, Piteleki, Reston VA
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USCG (G-MP-3/USP/82) Washington Dc; G-EOE-4 (T Dowd), Washington, DC; Library Hqs Washington, DC
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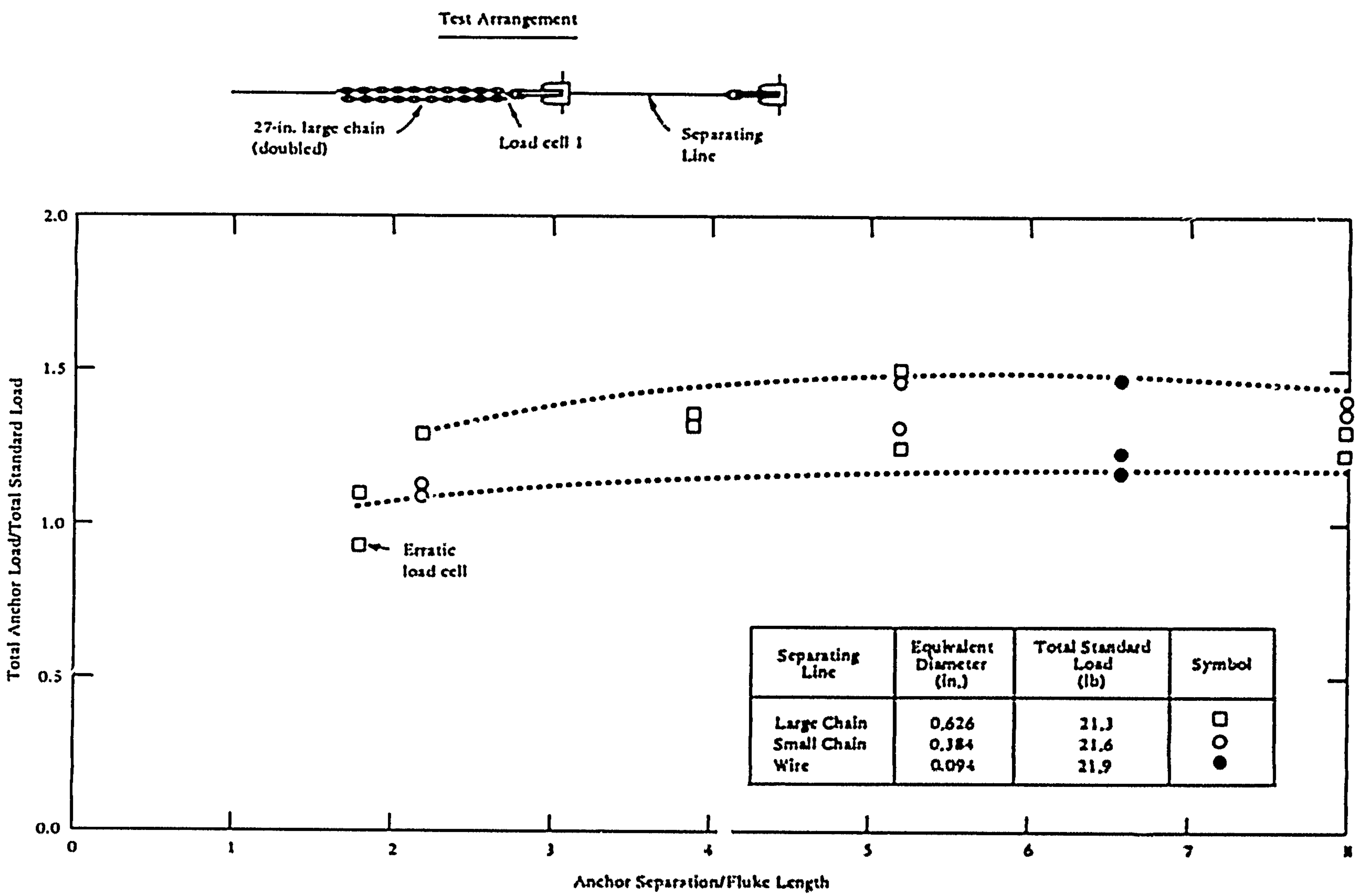

Figure 37. Summary tandem data for model STATO anchors in mud.

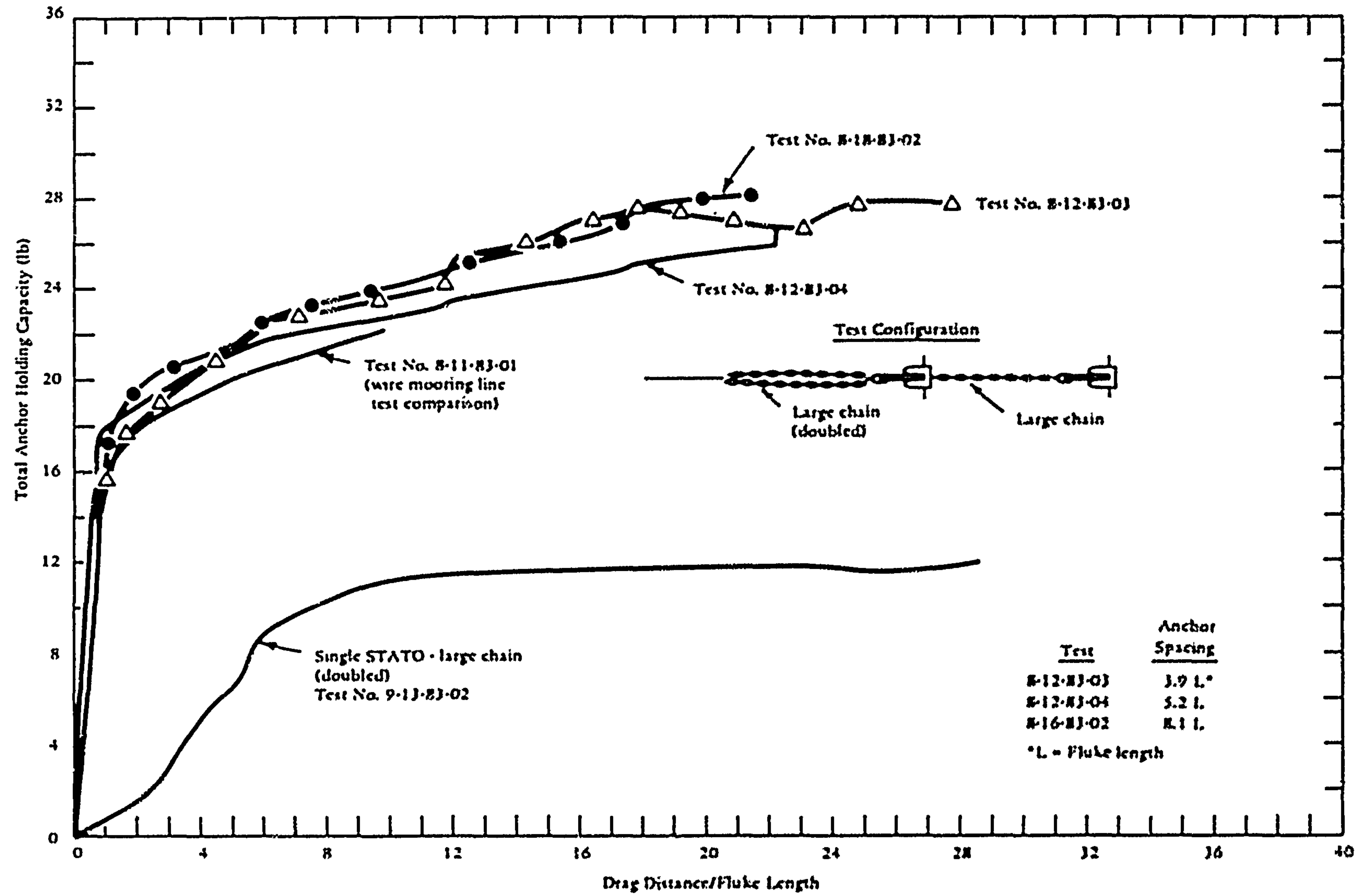

Figure 36. Total capacity versus normalized drag distance for model tandem STATO anchors in mud.

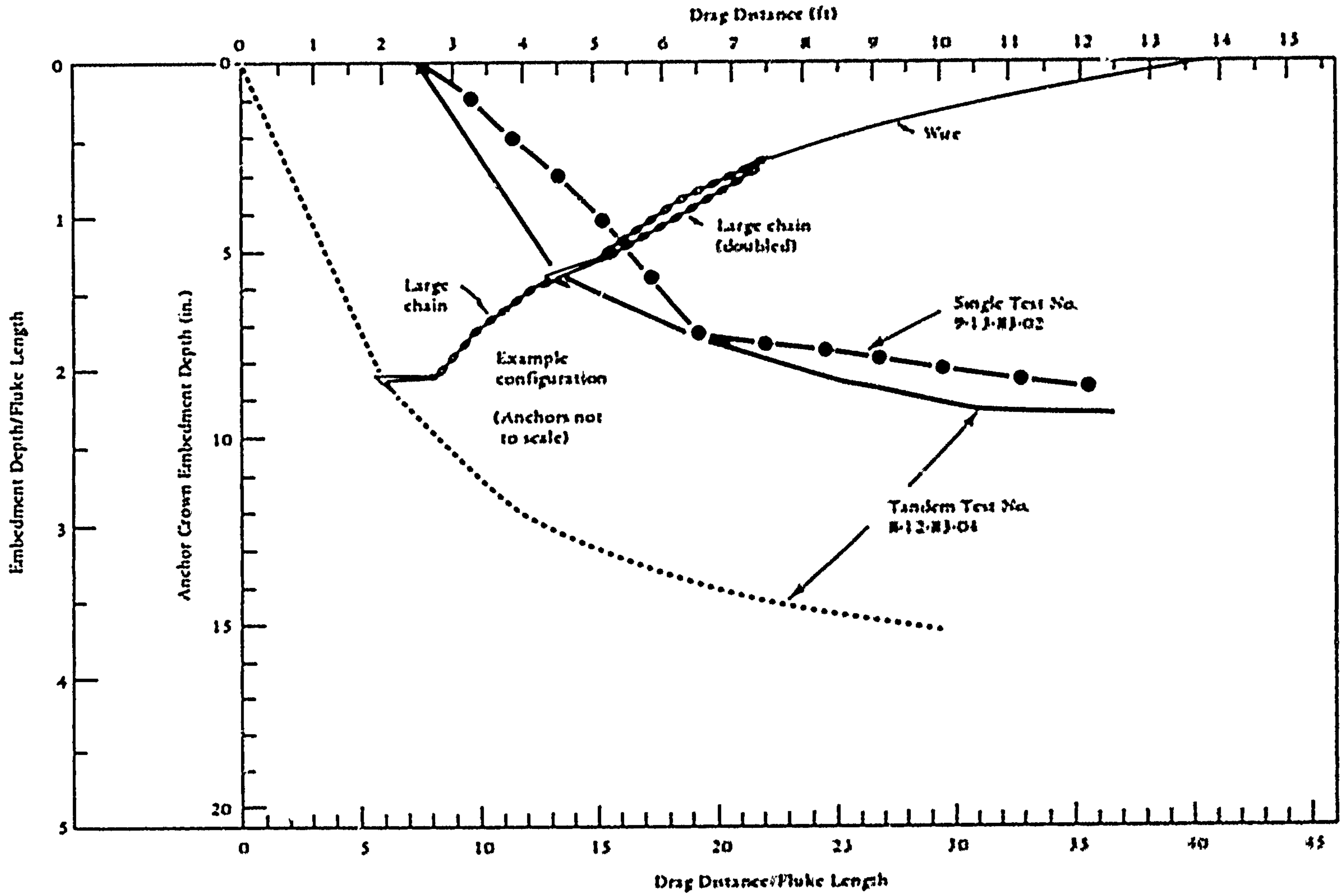

Figure 35. Tandem anchor system trajectory in mud at 5.2-fluke length anchor spacings.

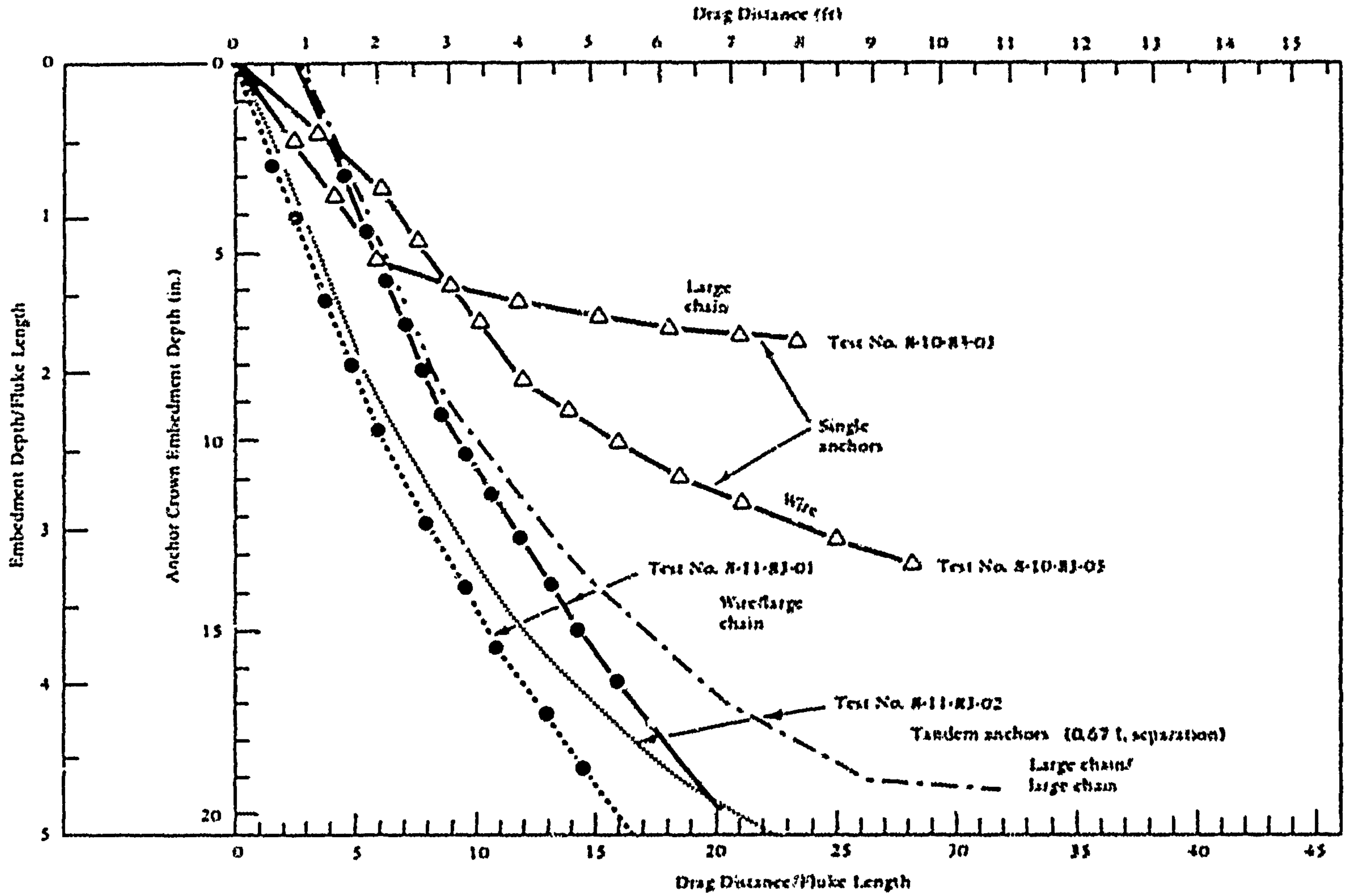

Figure 34. Comparison of single and tandem anchor system trajectories in mud.

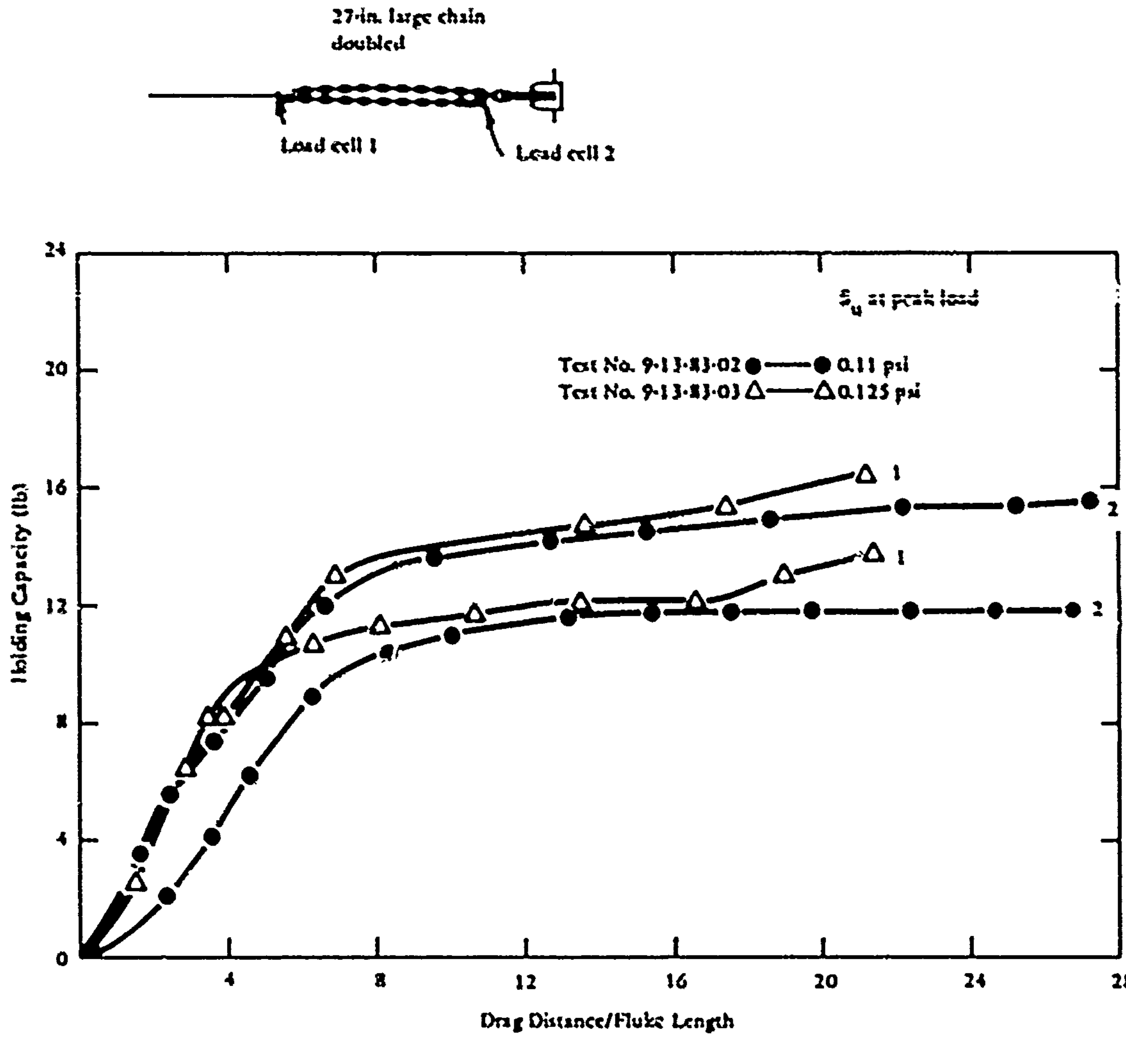

Figure 33. Single anchor tests in mud, showing load carried by chain portion of mooring line.